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Flat-Plate
Solar Array Project

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FSA Field Test Annual Report

August 1980-August 1981

Peter Jaffe
Robert W. Weaver
Robert E. Lee



December 15, 1981

Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
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Pasadena, California

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Aeronautics and Space Administration.**

The JPL Flat-Plate Solar Array Project is sponsored by the U.S. Department of Energy and is part of the Photovoltaic Energy Systems Program to initiate a major effort toward the development of cost-competitive solar arrays.

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ABSTRACT

A complete restructuring of Flat-Plate Solar Array Project field-test activity was done during the past year; its major element was redirecting emphasis away from collecting endurance data and toward the early identification and analysis of fundamental module problems. To support this shift and to accommodate an expected reduction in resources: (1) the 12 Continental Remote Sites have been decommissioned; (2) testing has been consolidated into a five-site network consisting of the four Southern California sites and a new Florida site; (3) 16 kW of new state-of-the-art modules are being deployed at the five sites; (4) testing of the old modules is continuing at the Goldstone site but as a low-priority item; (5) the major thrust of the new emphasis--early problem detection--will be accomplished by array testing of modules at the JPL site; (6) additional new testing capabilities are being added to the JPL site, which will elevate its operations to those of a field test laboratory for the simulation and investigation of real-use problems and the development of improved testing techniques; (7) a new key instrument is being fabricated, a versatile battery-powered array data logger, which will permit in-field diagnoses of arrays as large as 40 amperes and 400 volts. Restructuring is progressing on schedule.

A final set of failure and degradation data was obtained from the modules at the Southern California sites before they were relocated at Goldstone. The mean composite failure rate for all the modules (Blocks I, II and III) over the past five years is 2.0 percent per year. Considering the final two years only, the rate is 4.4 percent, suggesting a significant upward trend with age.

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SECTION I

INTRODUCTION

A major restructuring of Jet Propulsion Laboratory (JPL) field-test operations and facilities was effected during this reporting period. Its primary element, both philosophically and operationally, is the shifting of test emphasis from collecting endurance data to early detection and analysis of real-use problems and failures. The restructuring was effected for a combination of technical, logistical and financial reasons:

- (1) The impending deployment of many new state-of-the-art modules required enlargement of test sites and reallocation of test areas.
- (2) Most modules under test at the beginning of the reporting period represented old design technology; continued testing of these modules on a broad scale would be of questionable value.
- (3) Data collected to date shows a weak correlation between electrical failure and climate; benefits derived from testing in all environments are no longer sufficient to warrant the time and cost expended.
- (4) Failure mechanisms have appeared in real applications that have not arisen in qualification and endurance tests. There is an industry-wide need to develop testing techniques that address real-use failures.
- (5) A planned reduction in resources necessitated consolidation and a reassessment of priorities.
- (6) The evolution and improvement of module designs has outpaced the acquisition of endurance data because of the time required to collect the data. Field-test resources can be used better by focusing activity on identifying and investigating the fundamental causes of real-use operational failures.

Most of the work carried out in this reporting year, and the central theme of this report, is the restructuring of field-test activities. Highlights of the restructuring plan are presented in Section II; implementation details are outlined in Section III, and the implementation schedule is presented in Section IV. Although most of the activity centered on the restructuring plan and its implementation, endurance testing and other work continued. Section V contains a summary of the endurance data collected this year, and Section VI summarizes other ongoing work.

SECTION II
RESTRUCTURING PLAN HIGHLIGHTS

The 12 continental remote sites will be decommissioned. The test sites will be officially closed, and the Block II modules deployed at 11 of them four years ago will be sent to JPL where I-V curves will be obtained in the large-area pulsed solar simulator (LAPSS) facility and a final performance evaluation will be made. Through special arrangement with the cognizant engineer of the Sandia Laboratory test facility, the Flat-Plate Solar Array (FSA) Project endurance test modules deployed there will remain in place. These modules will be used primarily to augment, or to resolve uncertainties in, results obtained from the Goldstone modules, discussed below.

Test activities will be concentrated in a five-site network consisting of the four Southern California sites and a new Florida site. These sites, at JPL, Goldstone, Table Mountain, and Point Vicente in Southern California and at Cape Canaveral in Florida, will provide a good cross-section of environments and most of the important weather extremes. The Florida site is needed to provide the key weather extreme missing from the Southern California sites: a hot, humid environment. Past experience has shown this type of environment to be the most damaging to modules.

Testing of the old modules at the Southern California sites will be continued at an enlarged Goldstone site, but on a low priority. All of the old Blocks I, II and III modules at the other Southern California sites will be removed to make room for new modules. About 45% of these will be relocated to the enlarged Goldstone facility, where they will be tested on a time-available basis. After careful consideration, it was decided to continue testing these modules, if only in a limited manner. Three to five years of test time have been invested in them; it is conceivable that it takes five to 10 years of exposure before material changes affect performance. One type of module, the Spectrolab II, is of particular interest: it has many of the design features of the new modules, has been in the field for four years, has experienced no critical material changes and has exhibited very few electrical problems. If it continues to behave in this excellent manner, it will increase confidence in the feasibility of the 20-year-life goal. A small number of selected types of modules will be kept at JPL for close observation.

Testing will be started anew with a large deployment of Block IV modules. Approximately 16 kW of the new state-of-the-art modules will be deployed at the five sites. Half of these will be deployed at the JPL site. These modules and later deployments will be the nucleus of future work.

The major element of the restructuring plan, shifting from the collection of endurance data to early detection and analysis of fundamental problems, will involve five steps:

- (1) Testing will be conducted with modules under both individual and array-load conditions. To simulate real-use operations, a significant portion of the modules at the JPL site will be configured, loaded and tested in arrays. Through a reorganization of the data

system wiring, and with the addition of an array data logger, I-V data from the individual modules and from the complete array, will be obtained almost simultaneously.

- (2) The electrical and physical condition of each new module deployed will be thoroughly documented before it is placed in the field, and will be monitored carefully afterward.
- (3) Renewed emphasis will be placed on solving the fundamental problem of making accurate in-situ performance measurements. The field time required to detect degradation in a module is a direct function of the accuracy with which comparative I-V measurements can be made. Currently, normalized peak-power data obtained on the same healthy module on two different days may vary by as much as +3%.
- (4) An immediate investigation of a module whose performance is suspect or whose physical condition has changed will be undertaken. The investigation will be narrow, focusing on the specific problem, and will include one or all of the following: diagnostic tests at JPL, examination of similar modules at JPL and at the remote sites to ascertain if the problem is widespread; laboratory tests conducted by the FSA Failure Analysis group, and consultation with other experts in the FSA Project.
- (5) To broaden the scope of the activity, additional information about potential module problems will be obtained by maintaining close contact with field centers throughout the country.

Endurance testing will continue, but as a lower-priority item.

Assembling and reporting endurance statistics on the old modules and the new Block IV modules will be continued, but the frequency of this reporting will depend upon commitments to work of higher priority.

SECTION III

IMPLEMENTATION

A. TEST SITE NETWORK

Key features of the five sites constituting the new test network are summarized:

- JPL (Pasadena): Southwest urban, high-pollution environment. Hot summers, temperatures occasionally over 100°F (37.8°C) and mild winters, seldom below freezing. The site is near the northern perimeter of JPL at an elevation of 1250 ft (381 m). It is the largest and most thoroughly instrumented site, with a computer-controlled automatic data-acquisition system for obtaining module and array performance data, and weather and insulation data.
- Goldstone: Typical high-desert environment. Very hot and dry summers with clear skies. Temperatures below freezing in winter; there are occasional brisk winds. This site is near Barstow, California, at an elevation of 3400 ft (1036 m).
- Table Mountain: Typical Mountain environment. Heavy winter snows and mild summers. Strong gusty winds are experienced periodically; winds in excess of 100 mi/h (161 k/h) have been recorded. The site is in the San Bernardino Mountains at an elevation of 7500 ft (2286 m).
- Point Vicente: Typical southwest coastal environment. Damp mornings, clear afternoons, heavy salt spray. The site is on the Palos Verdes Peninsula in Southern California atop a 75-ft (23-m) bluff overlooking the ocean.
- Cape Canaveral, Florida: Typical southeast coastal environment. Hot and humid, corrosive salt atmosphere. The annual rainfall is about 60 in. (152 cm) and the mean daily humidity is over 75%; there are frequent thunderstorms. The site is at the Florida Solar Energy Center in Cape Canaveral, about 200 ft (61 m) from the water's edge.

To accommodate the new modules and to provide space for additional modules later, it was decided to increase the test capacity of the existing sites. This was accomplished by modifying the test frames to take advantage of the space between adjoining stands. With this modification, the available test area was increased by about 30%. New stands were also installed at Goldstone to accommodate the relocated Blocks I, II and III modules. Figure 1 shows the enlarged Goldstone site with the relocated old modules. The test frames in the southeast corner of the site belong to the FSA Project Encapsulation Task. A security fence is planned for the site.

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Figure 1. Enlarged Goldstone Site

B. NEW MODULES

The new state-of-the-art modules to be deployed will be of nine different designs--seven intermediate-load designs and two residential designs (see Figure 2). The two ARCO Solar Inc., intermediate-load modules are much the same; one was produced for the FSA Project on an experimental automated-assembly line, and the other was produced by conventional assembly. All but the ARCO Solar automated-assembly modules are from the FSA Block IV large-scale procurement.

The key design* and operating characteristics of the modules are presented in Tables 1 and 2, and Figure 3. Table 1 offers general information about the modules and Table 2 provides a breakdown of their internal electric circuits. Figure 3 (a through h) shows an edge-view cross section of each module, showing the different layers of materials used in their fabrication.

*At the writing of this report two designs, the Photowatt International, Inc., and the ARCO Solar residential, had not yet passed the Block IV qualification tests; the design information in this report must be taken in this context. It is possible that the two designs will have to be modified before they pass the qualification tests.

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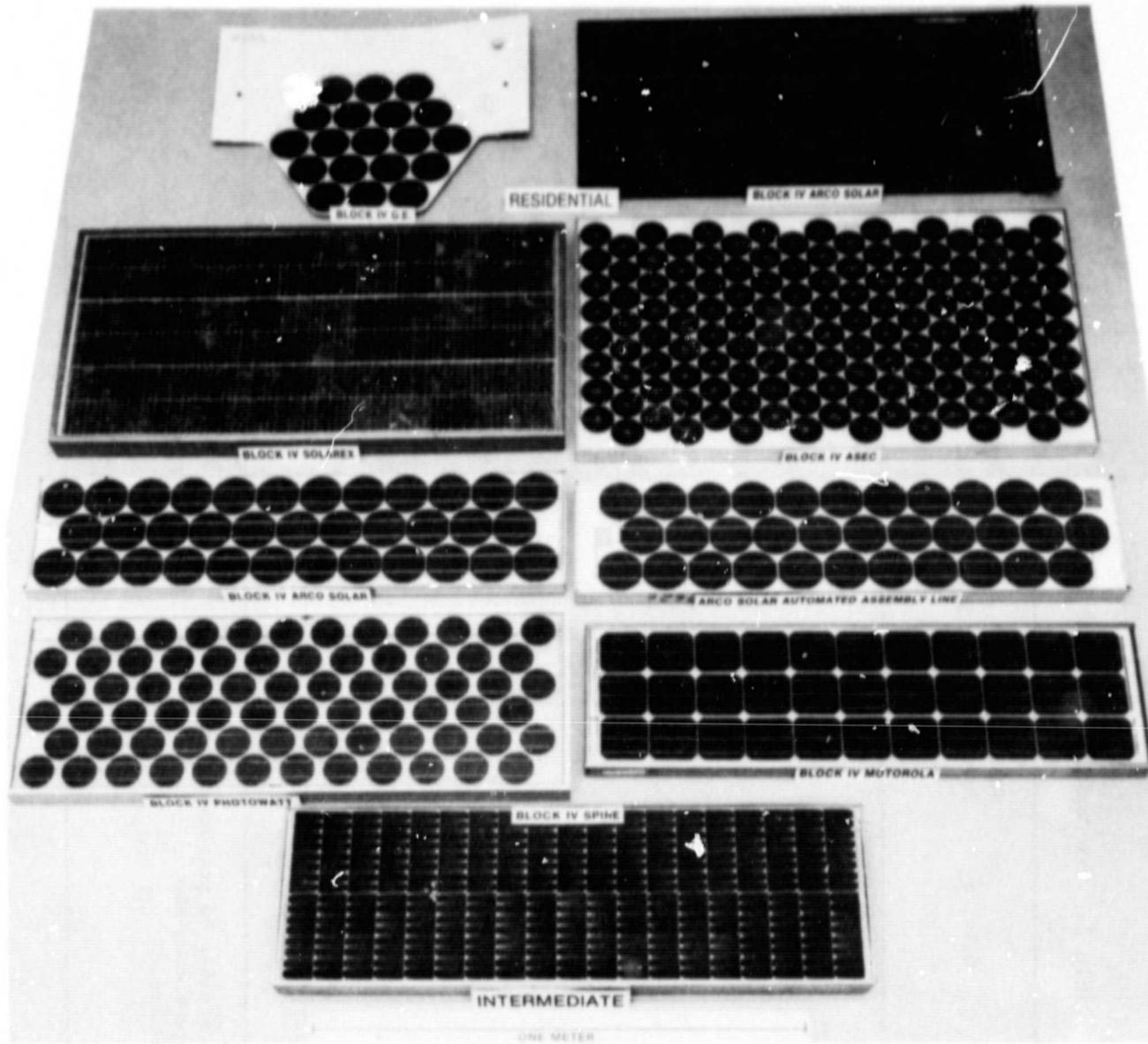


Figure 2. Prototypes of the New Modules (Actual Deployed Modules May Be Slightly Different)

There are many common design characteristics. All but the ARCO Solar residential modules have glass superstrates; all designs have redundant interconnects; all of the modules use Czochralski-type cells except the Solarex Corp. modules, which use polycrystalline-type cells, and many of the modules use series-parallel circuitry.

C. DEPLOYMENT PLAN

More than 375 of these new modules will be deployed at the five sites. Of these, 187 will be deployed in seven arrays at the JPL site. All of the

Table 1. New Module Characteristics

Part No.	Size, in	Nominal ^a Power, W	Cell Characteristics			NOCT ^b , °C
			Base Material	Size, cm	Metalization	
<u>Intermediate</u>						
ARCO Solar Blk IV	012110-E	1.22 x 0.30	32	Cz	10.0 (dia)	Printed Ag
ARCO Solar Automated	ASI-16-2000	1.22 x 0.30	32	Cz	10.0 (dia)	Printed Ag
ASEC Blk IV	60-3062-C	1.20 x 0.70	71	Cz	7.6 (dia)	Ti-Pd-Ag
Motorola Blk IV	MSP43040-G	1.20 x 0.36	33	Cz	10.0 x 10.0	Pd-Ni-Solder
Photowatt Blk IV	ML-196 ^c -C	1.20 x 0.44	33	Cz	7.6 (dia)	Ni-Solder
Solarex Blk IV	580-BR-L-C	1.20 x 0.64	53	SEMI-XTL	9.5 x 9.5	Ti-Pd-Ag
Spire Blk IV	058-0007-A	1.20 x 0.42	49	Cz	6.4 x 6.4	Ti-Pd-Ag
<u>Residential</u>						
ARCO Solar ^e	012431-F	1.20 x 0.58	51	Cz	10.0 (dia)	Printed Ag
GE Blk IV	47J254977G1-C	Hex, 0.48 side to side	14	Cz	10.0 (dia)	Printed Ag
						d

^aAt approximately NOCT; some values obtained on prototype modules.^bNOCT measurements obtained on prototype modules.

Assumed the same as the Block IV modules.

dNot available.

eProposed Block IV.

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Table 2. Electrical Configurations of New Modules

Module Type	Electrical Characteristics						Nominal Output ^a				
	Configuration			Diodes			I _{SC} , A	V _{CCP} , V	Peak Power (P _P), W	V _{at} P _P , V	I _{at} P _P , A
	No. of Cells Per Module	Cells in Series Per Substring	Substrings in Parallel Per Block	Blocks Per Module	STR BLK MOD	Diodes					
<u>Intermediate</u>											
ARCO (Blk IV)	35	35	1	1	-	1	2.4	20.6	34.7	16.5	2.1
ARCO (Auto Assem.)	33	33	1	1	-	1	2.4	19.2	32.0	15.8	2.0
ASEC	136	5	4	2	-	1	5.2	18.3	73.0	14.6	5.0
		6	4	4	6 in series						
Motorola	33	33	1	1	-	-	2.5	18.8	36.7	15.7	2.3
Photowatt	72	12	6	1	-	1	7.0	6.8	33.2	5.3	6.2
Solarex	72	1	2	36	-	1 36	6.8	13.5	58.8	11.1	5.3
Spire	108	3	3	12	-	2	3.6	21.5	55.6	3.3	17.2
<u>Residential</u>											
ARCO	60	20	3	3 (in parallel)	-	1 3	6.9	10.6	59.7	8.2	6.2
GE	19	19	1	1	-	-	2.4	9.3	14.4	2.1	6.9
Legend: ○ Cells □ Blocks											

^aAverages of at least four samples taken at NOCT.

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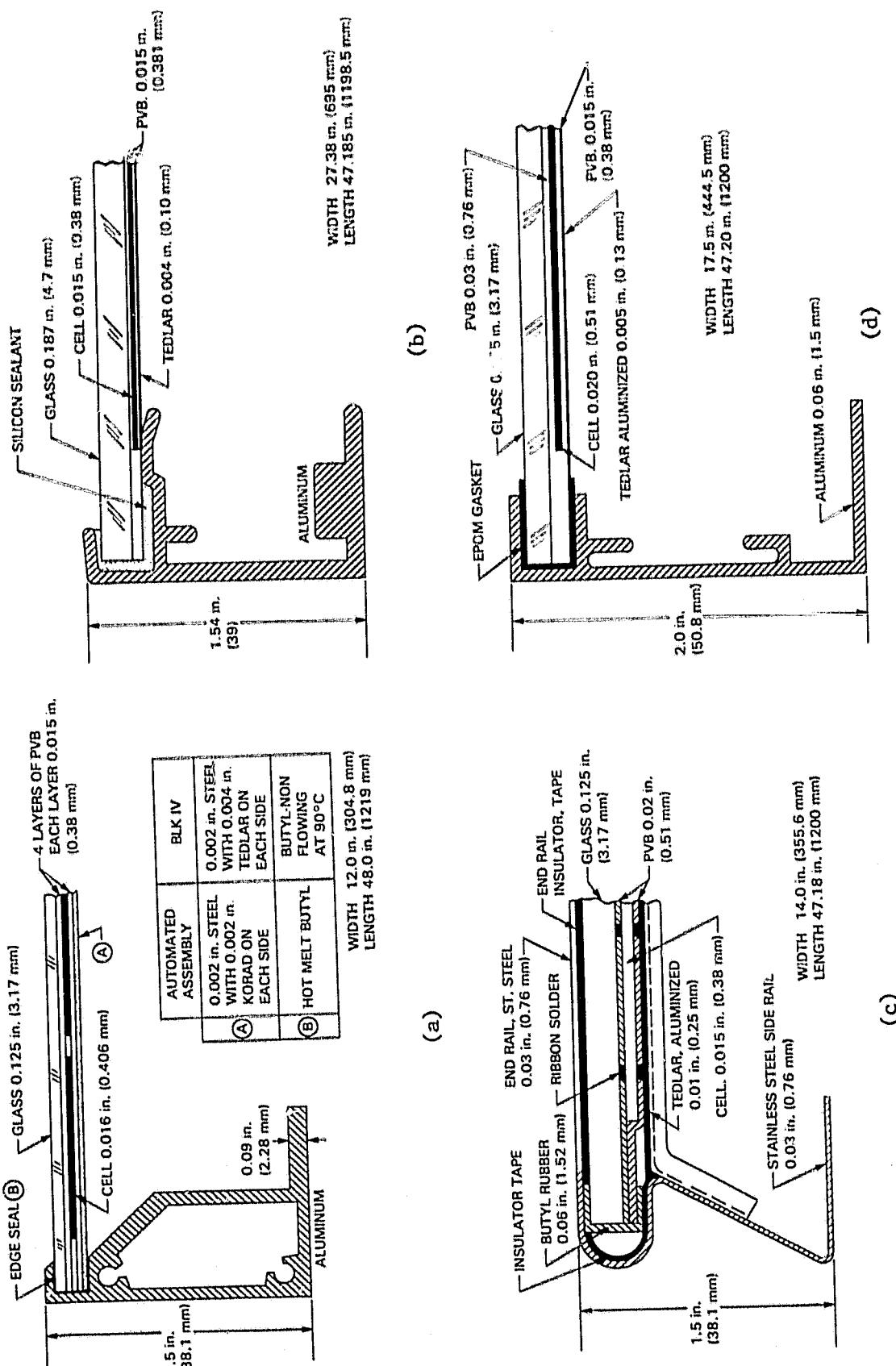


Figure 3. Cross-Section Construction of New Modules

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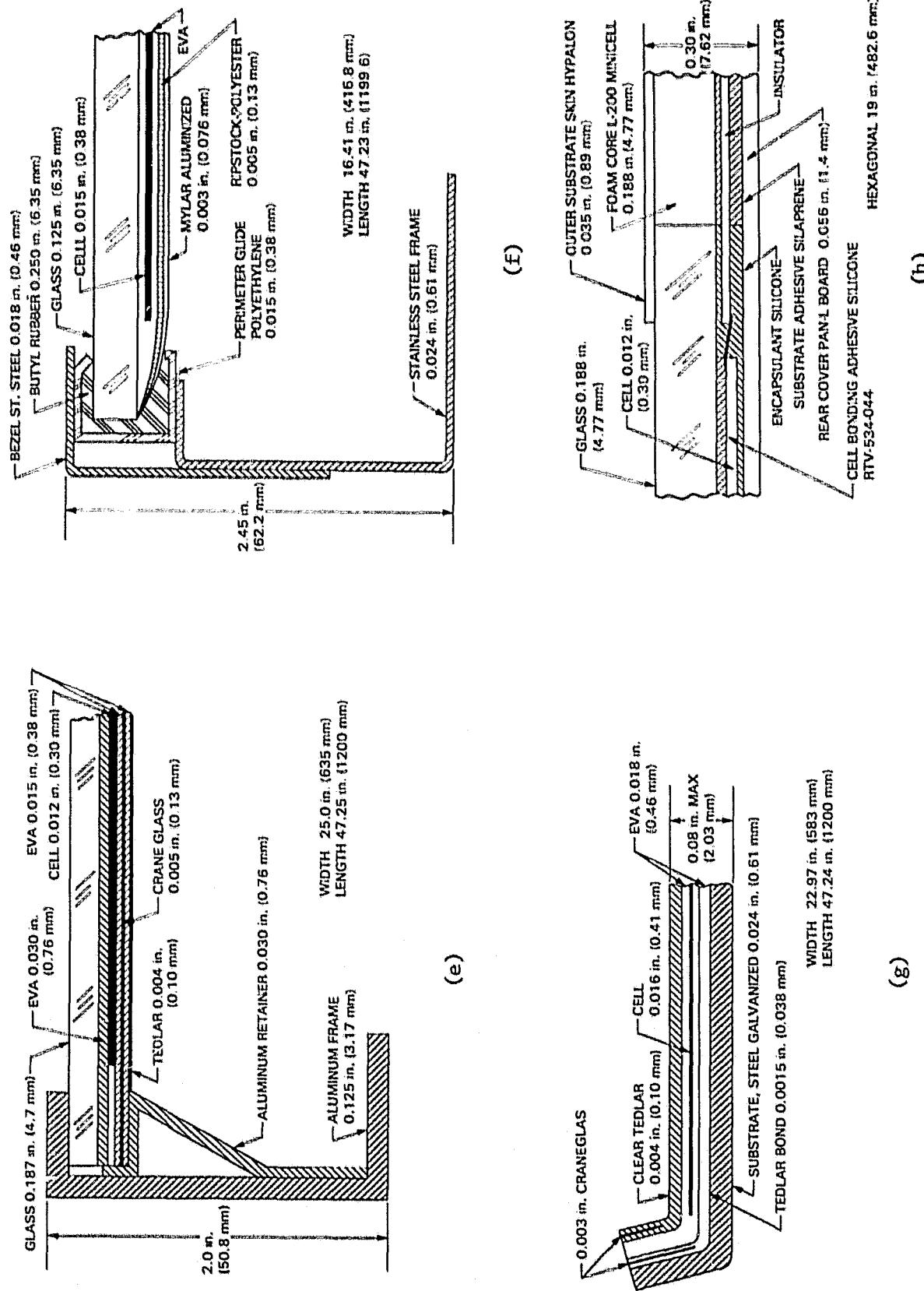


Figure 3. Cross-Section Construction of New Modules (Cont'd)

modules at the remote sites, and most of the non-array-configured modules at JPL, will be individually loaded and tested. Each site will have under individual load test six different types of Block IV intermediate-load modules.

The decision for individual load testing of these modules was a compromise. The number of new modules allocated was not sufficient, nor was there room available, to stock the remote sites with arrays. An option was to put different arrays at different sites, but it was believed that this would result in too many test variables to uncouple. For these reasons, and because of the desirability of testing arrays at JPL with its unique data-acquisition capability, it was decided to concentrate the array testing at JPL.

The individual-load modules will be loaded near the short-circuit current point to accentuate any cell-mismatch condition, a serious condition that has caused problems in the past. The arrays will be loaded near the peak-power point to simulate a real-use condition. Loading will be accomplished with fixed resistors. An option will exist to switch the arrays to different loads, both passive and dynamic, for special investigations.

Figure 4 shows the planned layout of the JPL site and Figure 5 contains a layout of the enlarged Goldstone site showing the planned location of the new modules. The deployment of new modules at Table Mountain, Point Vicente and Cape Canaveral will be the same as at Goldstone. A discussion of the JPL site is presented in Section III E.

Before deployment, a LAPSS I-V curve and a laser-scan record of each module will be made. The laser-scan data will provide a baseline record of the relative performance characteristics of each cell in the module. Basically, the laser scan record provides a comparison of the shunt resistance of individual cells in the module to the average shunt resistance of the series string of cells. Figure 6 shows a typical record. Variations in cell brightness correspond to different shunt resistances; at zero bias, bright cells have a higher shunt resistance than the average of the other cells in the string. Initially the record will reveal manufacturing defects, such as cracked or shorted cells. Subsequent data will be useful in detecting new cracked cells, cell changes, and metallization-contact and interconnect-integrity problems.

Once deployed, in-situ baseline I-V data will be obtained with the JPL data acquisition system, for JPL modules, and the portable I-V data logger, for remote-site modules. Follow-on electrical performance measurement will use the same instruments to minimize measurement errors.

D. ACQUISITION OF SANDSTROM I-V TRANSLATION CONSTANTS

Translation of field-test I-V data from one temperature and insolation to another is done with the Sandstrom equations.* These equations require

*Sandstrom, J.D., A Method for Predicting Solar Cell Current - Voltage Curve Characteristics as a Function of Incident Solar Intensity and Cell Temperature, National Aeronautics and Space Administration Technical Report 32-1142, Jet Propulsion Laboratory, Pasadena, California, July 15, 1967.

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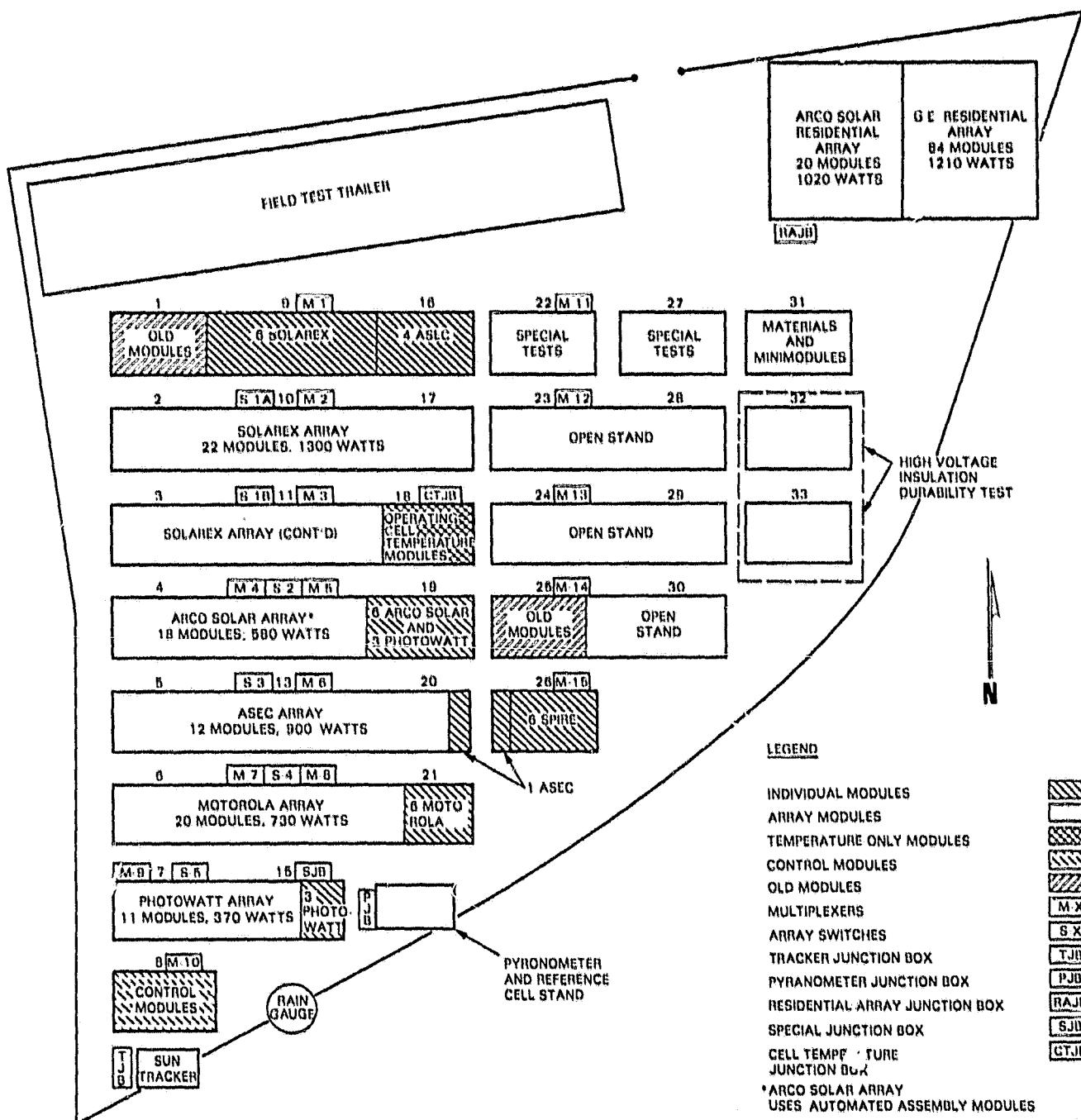


Figure 4. Planned Layout of JPL Site

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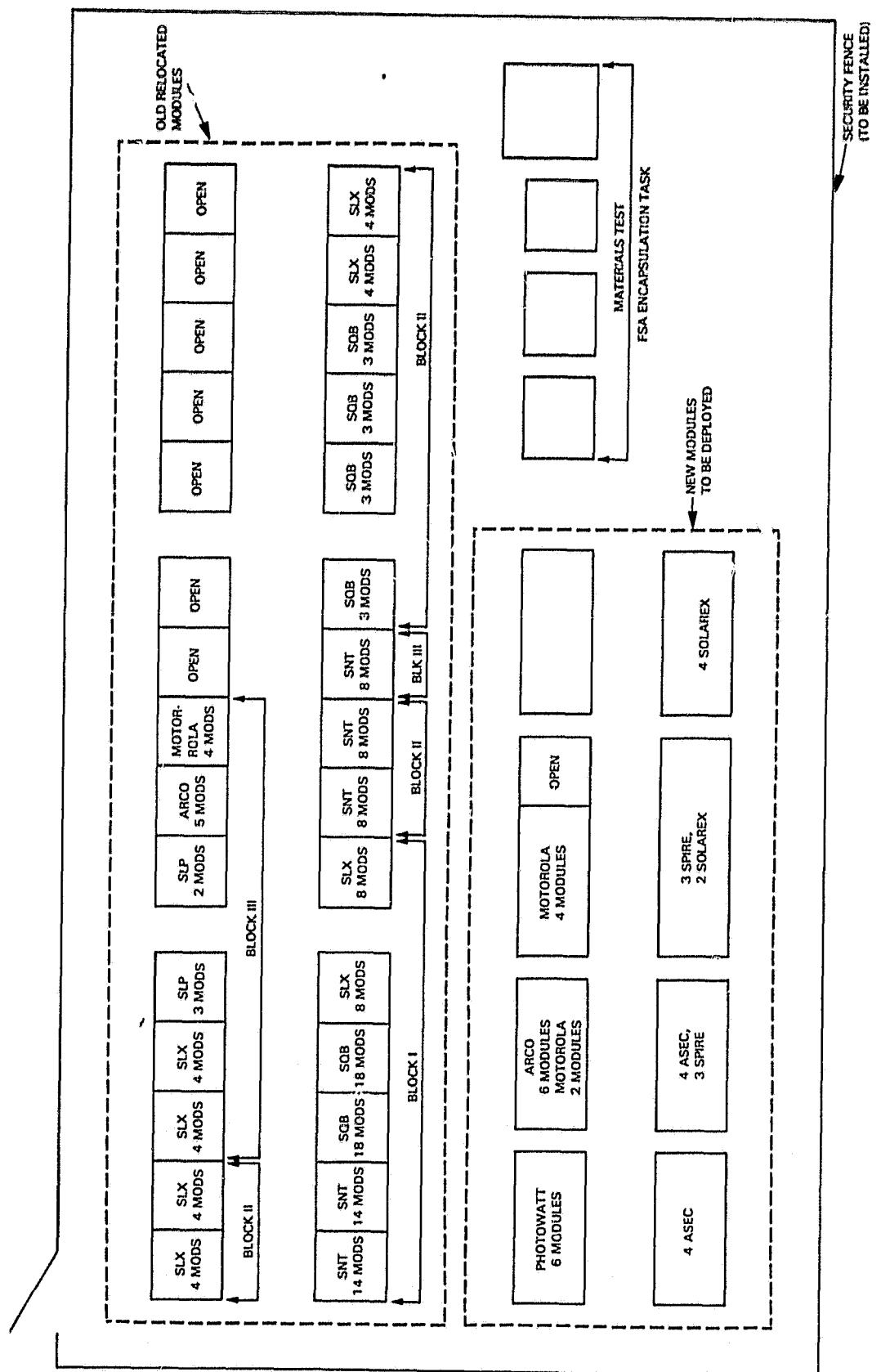


Figure 5. Layout of Enlarged Goldstone Site

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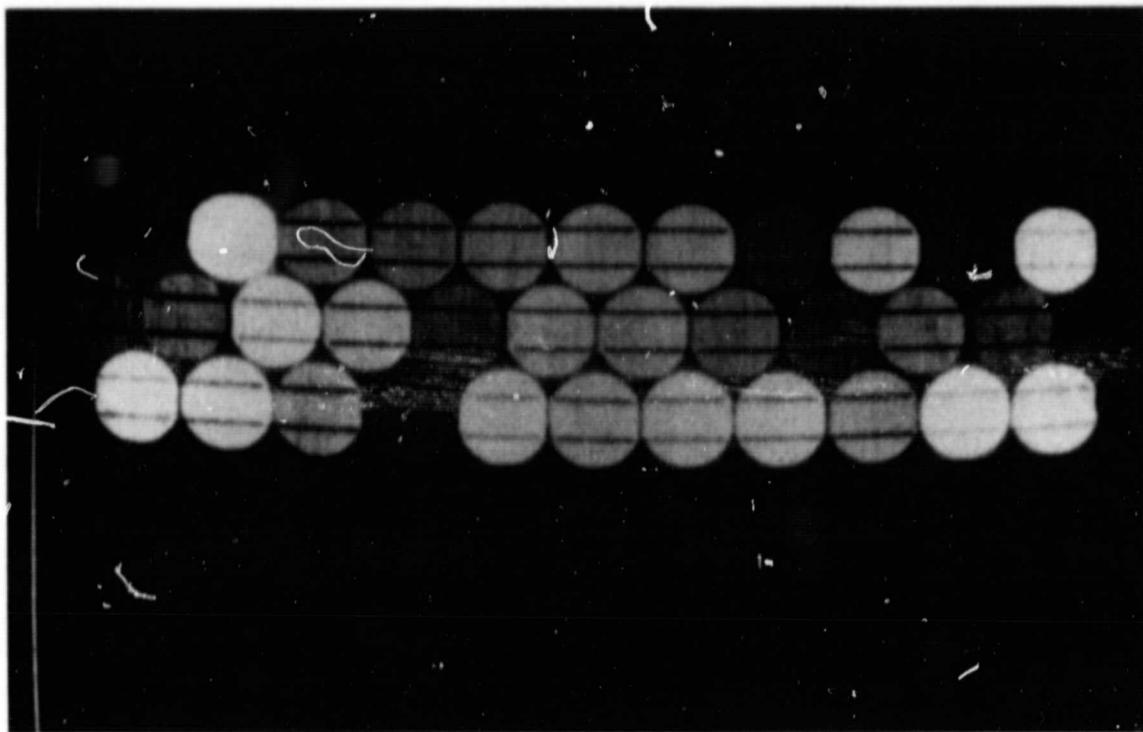


Figure 6. Typical Laser-Scan Record

four constants: a voltage-temperature coefficient, a current-temperature coefficient, series resistance and a curve-correction factor. In the past, uncertainty in the accuracy of the translated I-V data was attributed in part to a lack of confidence in the values of these constants.

Before deployment of the new modules, a program will be conducted to obtain as accurate a set of these constants as possible. The plan is to use a sample of eight to 10 modules of each type to obtain a good statistical base, and use the LAPSS system with the hot box to obtain data at different conditions. I-V curves will be obtained on each module at three conditions: 100 mW/cm^2 , 60°C ; 100 mW/cm^2 , 28°C , and 50 mW/cm^2 , 28°C . These data will then be numerically reduced to the four Sandstrom constants, and once the constants are determined, an accuracy analysis will be made by translating specially obtained I-V data and/or the data used to acquire the constants, from one condition to another. Information about expected translation accuracy for a population of the same type of module is of considerable interest to the photovoltaic community.

E. JPL SITE REORGANIZATION

Testing at the JPL site will play an even more important role in future field-test activities than in the past. All of the array testing, much of the diagnostic testing, and most of the technique development will be conducted at JPL. The physical layout and the electrical wiring of the site will be

modified. The purpose of these modifications are fourfold: to provide a facility for array testing, to better accommodate the new modules (which in general are bigger and operate at higher current levels than the old ones), to better utilize the available space, and to incorporate testing improvements that have evolved over the past five years.

1. Layout

The new intermediate-load modules will be deployed in four different test modes: as individually loaded modules, in arrays, as temperature reference modules and as control modules. The site layout is shown in Figure 4.

Six modules from each of the Block IV manufacturers will be mounted in the field and will be independently wired and loaded. Each of these modules will be connected, through the load side of a multiplexer channel, to a fixed-load resistor, and will sense this load at all times except during the data sampling period around solar noon. These modules will be mounted on Stands 9, 15, 16, 19, 20, 21, and 26 (see Figure 4). Two of the different types of modules will not be mounted contiguously as are the other four. The separated modules will be used to determine if location in the field has an effect on output and may be used for other studies such as diffuse sky shadowing (discussed later).

The location of the modules that will be mounted in arrays is shown in Figure 4. A more detailed description of these arrays is given in subsequent paragraphs in this section.

The modules that will be used as operating-cell-temperature references will be mounted on Stand 18. One of each manufacturer's intermediate-load-type modules will be included. This stand was chosen because it is located approximately midfield and should yield average field temperatures. Each module will be instrumented with four thermocouples. The thermocouples will be connected to the DORIC millivolt data logger housed in the trailer through the in-field cell-temperature DORIC junction box (CTJB).

The modules, one from each manufacturer, to be used as in-field control modules will be mounted on Stand 8. They will be covered with a special insulated removable enclosure to shield them from all atmospheric environmental effects with the exception of air-temperature cycling. When problems are reported relative to a particular module, data will be obtained from the appropriate control module to determine if the problem is generic or specific to the application or location of that module type. Also, if questions arise about the data system, these modules can be used to confirm or disallow a problem by removing them from the field and obtaining a comparative set of LAPSS data. An additional feature of the control stand is a special Universal module-mounting bracket. This bracket will be on the top side of the protective enclosure and can be used to obtain data on any module without having to go through the normal mounting procedure. There will also be a utility connector at this location to facilitate a quick connection with the data acquisition system.

The Blocks I and II modules to be retained at the JPL site will be mounted on Stands 1 and 25. On Stand 1 will be four Solarex Block II modules and eight Sensor Technology (now Photowatt) Block II modules. There will be 18 Block I, and three Block II Spectrolab, Inc., modules on stand 25.

The residential arrays will be mounted in the northeast corner of the field on a large tiltable structure that is several feet higher than any stands in the immediate area.

There are also several open stands and two special test stands. The open stands are for expansion of the field as more advanced modules become available for testing. The special test stands are available for short-term testing of individual or groups of modules. Special tests will include hot-spot testing, shadowed-cell tests, mismatched modules, etc.

2. Arrays

The JPL site reorganization plan calls for the installation of seven arrays. Two will be made up of Block IV residential modules, four of Block IV intermediate load-type modules and one of ARCO Solar intermediate-load automated-assembly modules. The location, number per array, and maximum output power of each array is shown in Figure 4. A description of the electrical characteristics of the arrays is given in Table 3.

All of the modules in the arrays will be wired in series with the exception of the General Electric Co. residential array, in which 21 groupings of four modules in parallel will be wired in series. In normal operations, the arrays will be connected to fixed-load resistors that have been selected to match the array mid-day peak-power point. Resistor values are shown in Table 3. In addition to the fixed resistive loads, provisions have been made to connect the arrays to other types of loads through a switch in the wiring circuit (details of the array wiring circuits are presented below). This feature will allow testing of the arrays under different loads, e.g., cyclic or constant-voltage, and will also serve as a connection point for obtaining array I-V data.

The five intermediate-load arrays will be wired in such a way as to allow the data system to collect individual module I-V data automatically, without manual switching. All of the arrays, including the residential arrays, will be instrumented to allow the DORIC system to collect single-point array current, voltage and power outputs. These data will indicate arrays' status relative either to their fixed loads or to an alternative load connected to them by the load switch. Array I-V curves will be obtained by connecting the portable array data logger (described in Section III F) to the appropriate alternative load/test connector.

3. Array Wiring and Switching

In order to obtain data on the arrays and the modules within the arrays, special wiring and switching circuits were designed. The intermediate-load array circuits have provisions for automatic and manual switching of the

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Table 3. Array Electrical Characteristics

Array Type	Modules in Array	Array Wiring Configuration	Array Electrical Characteristics*					Fixed Load Resistor (Ω)
			V_{OC} (Volts)	I_{SC} (Amps)	Max. Power (Watts)	V_{OP} (Volts)	I_{OP} (Amps)	
Arco-Solar (Auto. Assembly)	18	All In Series	345	2.4	570	284	2.0	142
ASEC	12	All In Series	220	5.2	875	175	5.0	35
Motorola	20	All In Series	376	2.5	720	314	2.3	137
Photowatt	11	All In Series	75	7.0	360	58	6.2	9.4
Solarex	22	All In Series	295	6.8	1295	244	5.3	45
Arco-Solar Residential	20	All In Series	212	5.9	1020	164	6.2	26
GE Residential	84	4 in Parallel 21 in Series	195	9.6	1220	145	8.4	17

*At NOCT

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array power circuits; for automatic and manual in-and-out switching of the modules in the arrays for I-V data acquisition and for acquiring ongoing array output data; for module interconnection controls, and for optional loading and/or testing of arrays and modules. The residential array circuits contain fewer options; they have provisions for manual switching of the array power circuit, for acquisition of array output data, and for optional loading and/or testing of the arrays. An ammeter, voltmeter and wattmeter are also included in the circuit for the visual observation of the array output status. These meters indicate the current through, the voltage across, and the power dissipated by the load. All of the circuitry and switches will be located in the multiplexer and switch boxes shown in Figure 4, with the exception of the computer-controlled power-circuit switches, which will be located in the trailer next to the computer. The visual meters for each array will be mounted in the door of the switch box assigned to that array.

a. Intermediate-Load Arrays. A typical array/module switching schematic for the intermediate-load arrays is shown in Figure 7. Each module in the array will be connected to its own three-position switch (SW-1, SW-2,

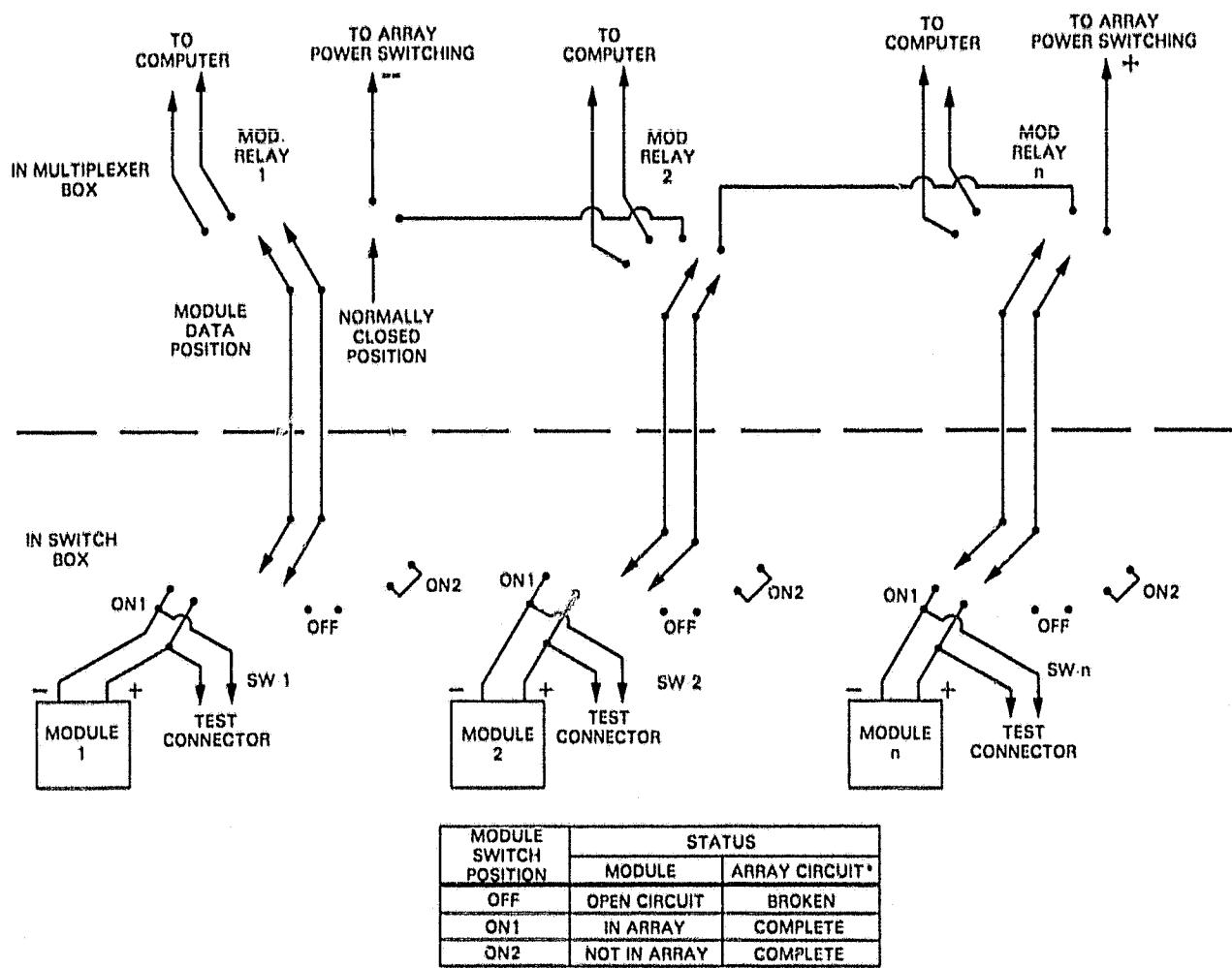


Figure 7. Array/Module Switching Schematic

and SW-n in Figure 7), and to a test connector on the switching panel (shown in Figure 8 as J1 through J14), which is located in the switch box.

The positions of these switches are denoted as ON1, OFF and ON2. When a switch is in the ON1 position, the module connected to that switch is part of the array circuit. The OFF position puts the module in an open-circuit state and the array circuit in an open condition. Any module switch in the OFF position will break the array circuit. The ON2 position also puts the module in an open-circuit state but leaves the remainder of the array circuit complete minus that module. The number of modules in the array can be controlled by the appropriate positioning of these switches without changing any wiring. The OFF and ON2 positions also can be used when a module is to be replaced.

The modules are wired into the array inside the multiplexer boxes. The wires from the switch in the switch box are connected to a computer-activated, two-position relay in the multiplexer box. When I-V data are obtained on a module, the computer activates its relay and switches the module from load position to data position. When none of the relays is being activated by the computer (the normally closed position in Figure 7), and none of the module switches is in the OFF position, the array circuit is completed through the wiring between relays. Even though the arrays are nominally series-configured, series-parallelizing of the array circuit can be arranged by changing the wiring between relays.

Completion of the array circuit is controlled by the array power switching circuit shown in Figure 9. This circuit consists of a power control section, a load control section and an array-output monitoring section. The output monitoring section includes the connections to the computer for sampling the current and voltage output of the array, and the three meters that indicate the voltage, current and power output of the array. The load control section is a manual switch that will connect the array to either the fixed-load resistors or to a connector that can be used to obtain an I-V curve with the array data logger or for connecting with an alternative load. This switch can also be used to open the array circuit. The power control section consists of a power switching transistor, a power supply for the transistor, a manual switch in the transistor circuit and a computer-controlled switch in the transistor circuit.

b. Operation of Intermediate Load Arrays. With the array circuit turned off, using the manual power circuit control switch, the modules that are to be included in the array circuit are selected and the appropriate module switches are turned to the ON1 position. The load control switch is then turned to the desired position and the power circuit control switch is turned on. The array circuit is now complete and connected to the desired load or, if array I-V data are to be taken, connected to the array data logger through the alternative load/test connector. When module I-V data are to be taken, the computer automatically turns off the power to the power-switching transistor, thus opening the array circuit. As each module is selected for interrogation, the relay to that module is switched to the module data position and the I-V data are taken. Upon completion of data taking, the relay is

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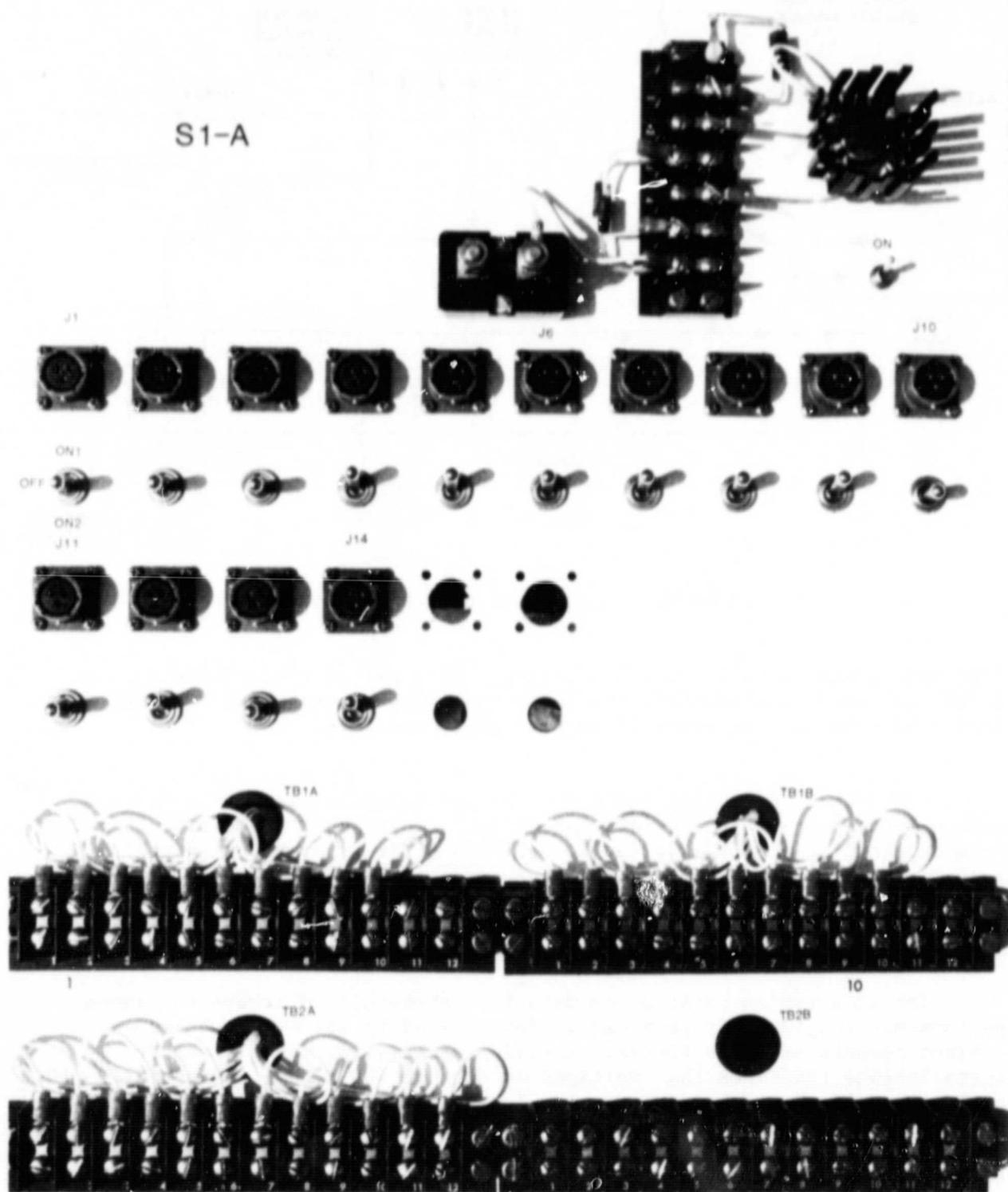


Figure 8. Array/Module Switching Panel

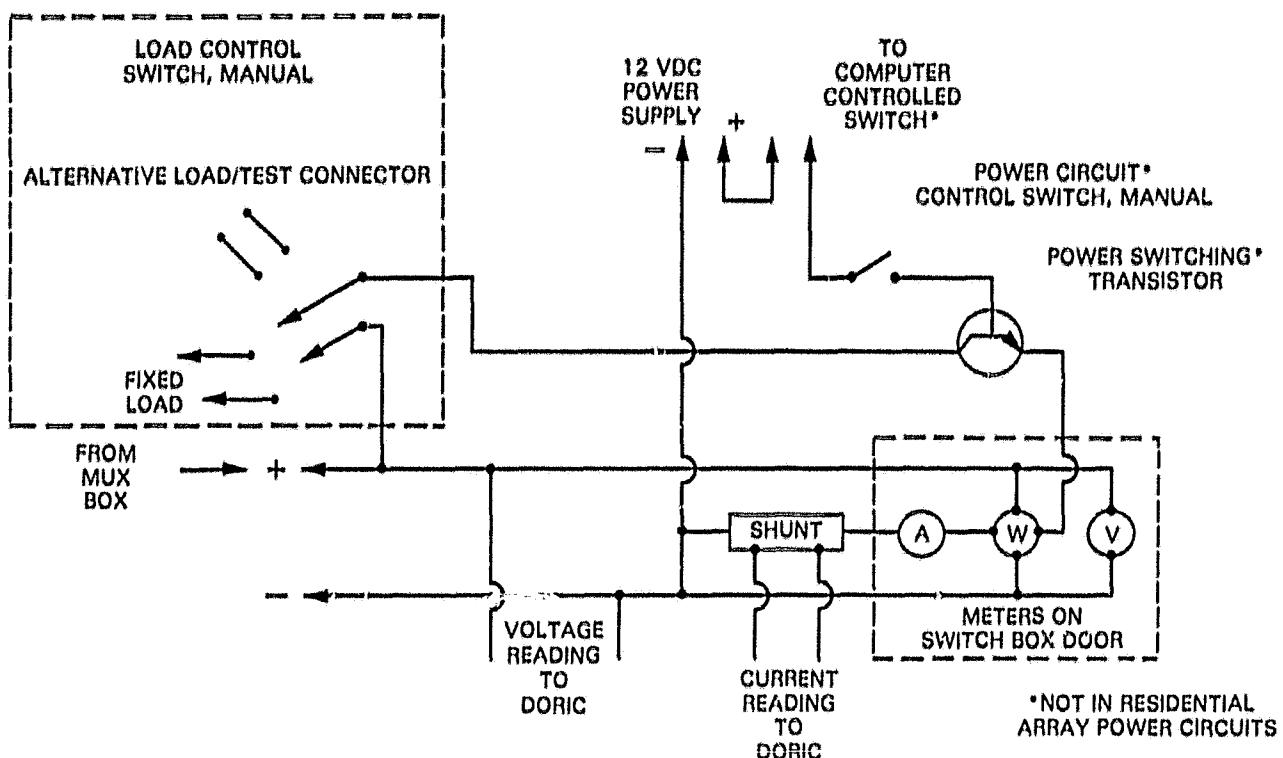


Figure 9. Array Power Switching Schematic

returned to the normally closed position. When all of the modules in the array have been interrogated, the power to the power-switching transistor is turned back on and the array circuit is again complete.

c. Residential Arrays. No provision is made for individual module monitoring in the residential array circuits and, therefore, there are no module switches or relays in this circuit. The array power switching contains only the load control and output monitoring sections described above.

F. ARRAY DATA LOGGER

The acquisition of accurate data from photovoltaic arrays to assess performance and identify problems is complicated by the high voltage and current outputs of these arrays. A review of existing and planned PV installations indicates that voltages as high as 400 V and currents up to 40 A could be realized at the array string level. The arrays being installed at the JPL site will have voltage levels ranging from 50 to 320 V and currents up to 9 A; these levels cannot be handled by the existing data system. Early in the planning phase of the site restructuring it became apparent that there was a need for an instrument that could acquire accurate data at these levels.

In March of 1981, the problem and a set of specifications was presented to the JPL Instrumentation Section (351). They developed a preliminary design

and were subsequently commissioned to complete the design, fabricate the equipment, develop the required software, test the equipment and prepare the necessary documentation. Fabrication began in June and the equipment is due to be delivered in January 1982.

The new system will be battery powered and portable, and will be able to acquire, compact, display and store I-V data from solar arrays as large as 400 V, 40 A. It will have a high level-language programming feature (BASIC), which will allow the user to expand its capability.

The system will be constructed in four units: a microcomputer unit; a small portable, battery-powered terminal with an LCD display; a load and array measurement unit, and a battery unit. A system block diagram is shown in Figure 10. These four units will be contained in 3-Zero brand cases. The load and battery cases will be built to withstand shipment as luggage. The microcomputer unit will be briefcase-size and will be able to fit under any airline seat.

Within the microcomputer unit will be the central computer-controller for the system. Provisions will be made for six auxiliary data input channels: two for measuring module and ambient air temperatures, two for pyranometer data for insolation measurements, and two for reference cell data. These data are required to adjust the I-V data to a standard reference condition. The microcomputer unit will also include: the battery charger and line power supply, the power control, the real-time clock, the interface to the load unit, and RS232C interfaces to the data terminal and plotter. Field power will be supplied

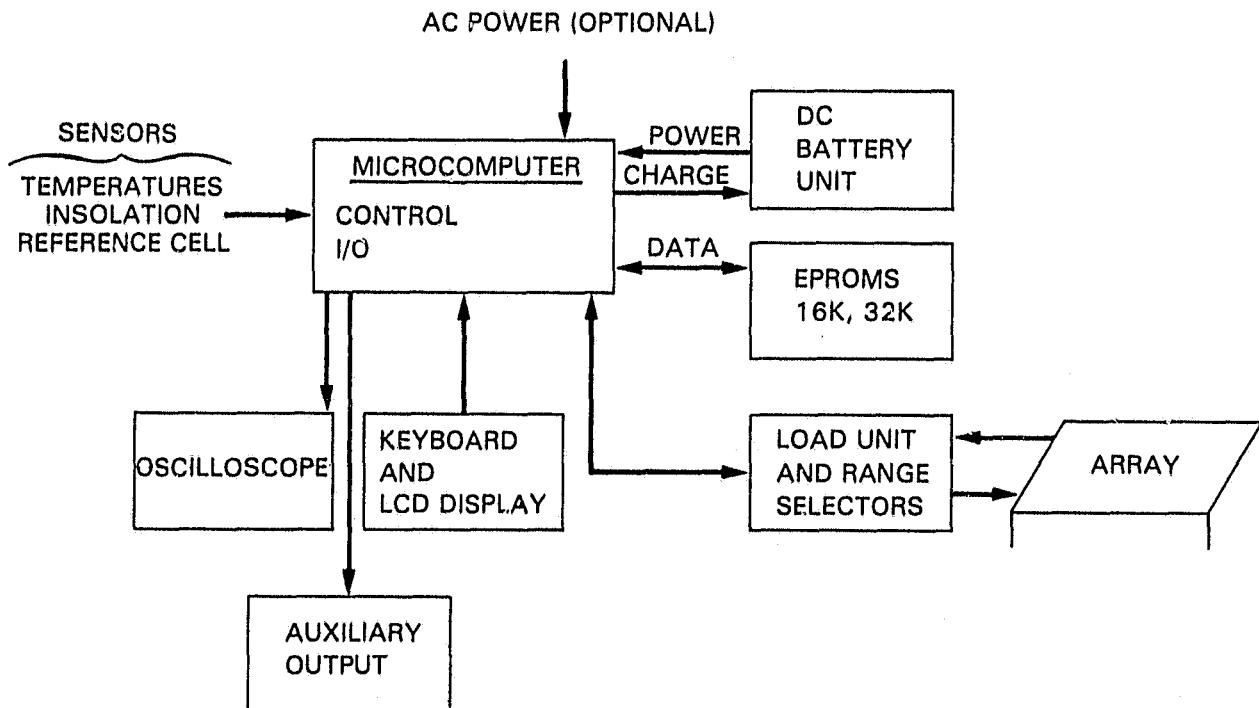


Figure 10. Array Data Logger Schematic

by the battery unit. The microcomputer will be able to store data on an EPROM module in the same format as the existing I-V data logger, and will be able to read and unpack data stored on an EPROM module and make the data available to a BASIC program. EPROM modules will also be used to store user-generated BASIC programs. The microcomputer unit will also be able to convert just-acquired I-V data into X-axis and Y-axis voltages for field display on any standard oscilloscope for verification before storage.

Control of the microprocessor unit will be handled mainly through the portable, battery-powered terminal. This terminal will be stored in the same case as the microcomputer unit. It will be removable and can be connected to the microcomputer unit by cable. The system battery will supply the terminal power. Commands to the system will be made using the keyboard. A 64-character LCD display will provide numerical output and user prompt.

The load for the solar module or array will be provided by a bank of capacitors in the load unit. This unit will also have all necessary circuitry to control data acquisition and data transfer to memory in the microcomputer unit. The microcomputer will control the load unit by commanding the acquisition process to start. The load unit will also contain the necessary current measurement shunt resistors. The shunts will be selected for use by manual high-current switches. Manual switches will also select the voltage range to be used during data acquisition.

The batteries will be contained in a separate case. They will be connected to the microcomputer unit to power the system. Gel cells will be used, to allow recharging. The charger will be located in the microcomputer unit.

For field operation, the units will be interconnected and powered. Data acquisition can take place as requested by the operator through the portable data terminal. After acquisition, the I-V data will be corrected for channel calibration factors, compacted and made available to an X-Y oscilloscope display. The V_{oc} , I_{sc} , fill factor, and peak power, and other measurements will be available for display on the data terminal at this time. Upon request, the data from the acquisition will be stored on an EPROM module in the same format used by the existing I-V data logger.* This format is compatible with the existing interface and software for the field-test PDP-11 computer.

The logged data can be recalled from the EPROM modules processed and analyzed by user-written BASIC programs. These programs will have been written on the system using a standard data terminal and stored in one or more EPROM modules before the field trips. BASIC programs could be written to plot the processed data, print it on a printing data terminal, or compare data from several data runs. Using these auxiliary programs, comparisons between baseline data and just-obtained data can be made to determine if any changes in array performance have occurred.

*A description of the existing I-V data logger can be found in the LSA Field Test Annual Report August 1979-August 1980, Peter Jaffe, Jet Propulsion Laboratory Document No. 5101-166, DOE/JPL 1012-52, December 30, 1980.

The array data logger will be used to collect I-V data from the arrays at the JPL site. The data taken will be transferred to the PDP-11 computer data bank for comparison with the individual module data taken by the existing automatic data system. This allows for the timely identification of module and array problems and performance degradation. Additionally, this rapid data acquisition and reduction capability will provide a tool for problem analysis.

The array data logger and trained operators will also be available for acquiring data at other installations when arrangements are made with the JPL Photovoltaics Technology Development and Applications Lead Center.

G. TEST OPERATIONS AND DATA ACQUISITION AT THE JPL SITE

The collection of data at the JPL site will remain much as before. Electrical performance data will be obtained daily on each module at solar noon, except those in the residential arrays, and routine weather and insolation data will be obtained every five minutes. Weather data will be obtained around the clock and insolation data from sunrise to sunset. Daily array data will also be obtained. Before and after acquisition of the daily I-V data, the current through and voltage across the array load resistors will be measured. Twice a week a complete I-V curve will be made on each array with the array data logger.

The daily acquisition is done automatically. A breakdown of the automatic weekday sequence is shown in Figure 11. Major events occur at 10 seconds after midnight, when the daily activities are scheduled and the weather task is started for a new day; at sunrise, when the tracker and insolation tasks are started; at solar noon, when the array load data and module I-V data from the field are collected; at 20 minutes after solar noon, when the just-collected I-V data are normalized and transferred to a holding file; at sunset, when the insolation task is stopped and the tracker task drives the tracker to the sunrise position for the next day, and at midnight, when the weather task is stopped. Once a day the hard-copy summary tasks (SUMAR1, 2, 3, 4 and 5) are run. The summaries are listed on the line printer. On weekends and holidays, the routine daily data is still collected but the line printer is inhibited and the summary tasks are cancelled. These are run the morning after the weekend or holiday. Approximately twice a week the data are stored in four files: the Weather Data File (WDF), the Pyranometer Data File (PFD), the Comparison I-V Data File (CDF), and the Array Data File (ADF) are manually archived. All data are permanently archived on tape.

Six operational changes related to the collection of data will be instituted:

- (1) Reference cells used to determine effective irradiance will be of the hermetically sealed, glass-encapsulated type. These will be installed in the open adjacent to the pyranometers (see Figure 4). The old reference cells did not have protective encapsulants and were enclosed in pneumatically-sealed cylinders. The new ones will more closely match the field of view and the optical characteristics of the modules. The new reference cells, which,

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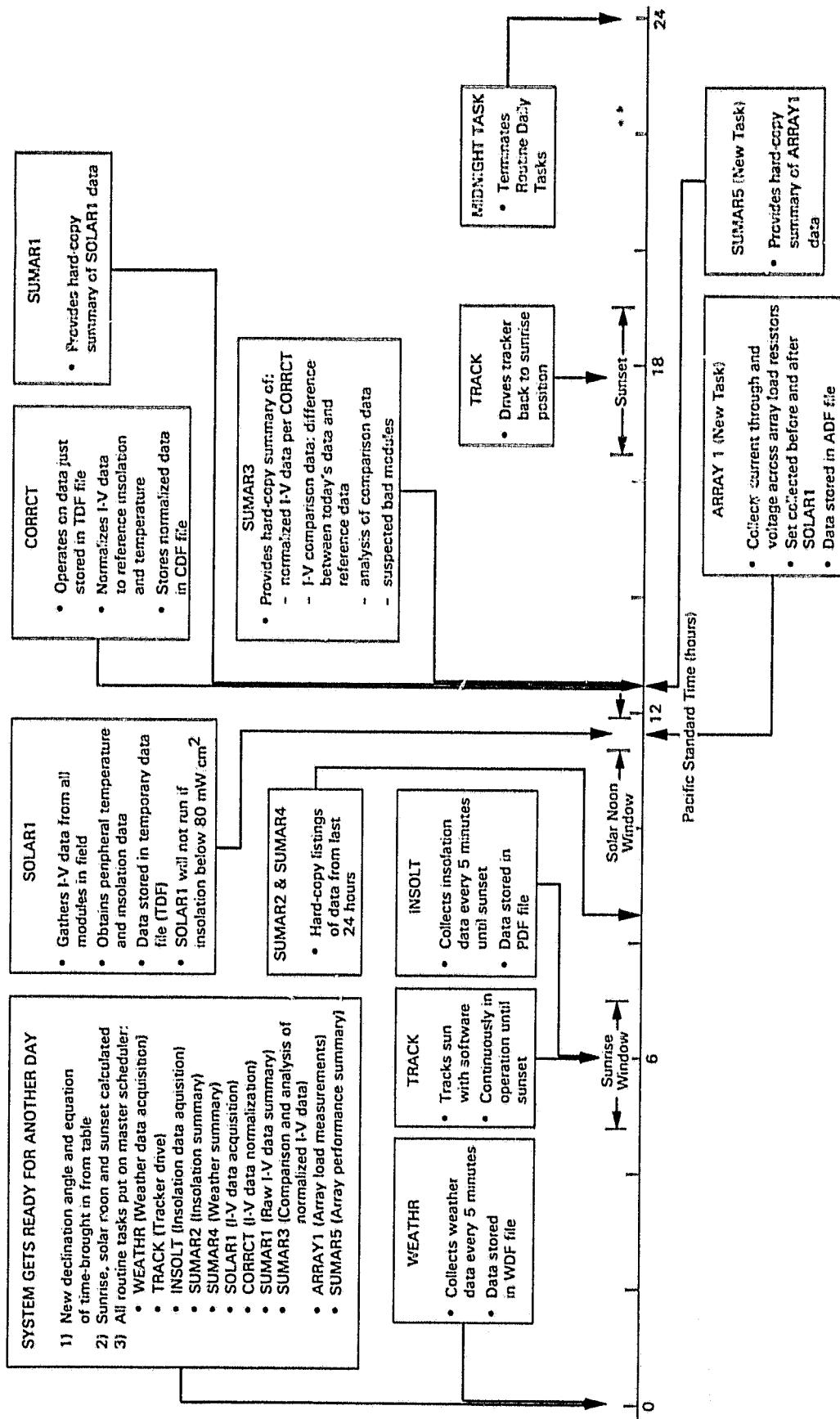


Figure 11. Automatic Weekday Data Acquisition

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as before, will be fabricated and calibrated by the Performance Measurements group of the Project, are shown in Figure 12. The reference cells are made as follows: The basic 2 x 2-cm cell is bonded to the bottom of the black anodized central cavity with RTV-560. The cavity is then sealed with a 1/16-in. (1.6-mm) piece of fused silica, leaving a slight space between the silica and the cell. Once the fabrication is complete the cavity is purged with nitrogen and the purge hole sealed. For a nominal cell thickness of 0.030 in. (0.76 mm) the unobstructed view angle is about 155°.

- (2) Module cell temperatures used to translate the I-V data will be obtained from a set of modules specifically deployed for that purpose. These modules, one of each type, will be located mid-field on Stand 18 (see Figure 4). Four thermocouples will be attached to each of the modules, three directly to the backs of cells at different places on the modules, and the fourth to the back of the substrate material behind one of the other thermocouples. This last thermocouple will provide information about the cell and module-backside temperature. The three direct cell temperature readings will be recorded each time an I-V curve of a module of its type is obtained. The average value will be used for translating the data. These modules will normally be in an unloaded condition.
- (3) The modules will be tilted to the local latitude, 34°, throughout the year. Two years ago, in an effort to reduce measurement errors, a schedule of tilting the modules was instituted in order to keep the irradiance incidence angle below 10°. An investigation last year concluded that the diffuse shadowing by the more southerly situated modules of the more northerly ones introduced an error greater than was caused by large incidence angles.

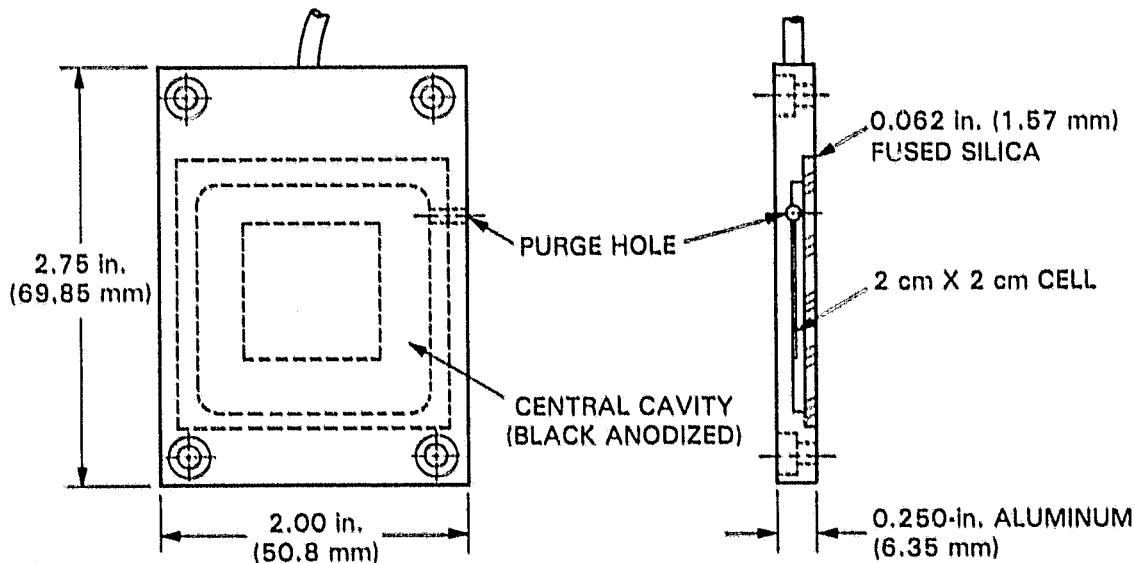


Figure 12. New Reference Cell Design

Tilting the modules at a steep angle in the winter was actually counter-productive. As a result, it was decided to eliminate the tilt schedule and keep the modules tilted at an angle equal to that of the local latitude.

- (4) I-V data comparison summaries will be made through SUMAR3, the program that provides a daily hard-copy comparison of each module's electrical performance with its performance at installation, which will be modified to yield additional information. Experience has shown that although the key electrical performance parameters, short-circuit current and peak power, may vary by as much as $\pm 3\%$ because of reference cell-module mismatch and data translation problems, the variation of an individual module's performance, in comparison with the other members of its family, is small if the module has not degraded. To take advantage of this observation, the program will be modified to compare each module with its family average and, using a screening criterion, flag suspected modules.
- (5) Insolation data obtained will be far more comprehensive than in the past. Six different sets of irradiance-characteristics data will be collected routinely: horizontal, tilted and tracked pyranometer data; normal incidence pyrheliometer data, and turbidity and water-vapor data. SUMAR2, the insolation summary program, will be modified to reflect these changes. Details are presented in Section VI.
- (6) Weekly physical inspection of all of the modules will be made visually. Anomalies will be monitored carefully, and detailed follow-on inspections will be performed by field test or quality-assurance staff members.

H. DATA ACQUISITION AT THE REMOTE SITES

Three or four times a year, I-V data will be obtained on each of the newly deployed modules at the Southern California remote sites with the portable I-V data logger. I-V data will be taken twice a year at Cape Canaveral. Two sets of data, taken on two different days, will be obtained on each visit to Cape Canaveral. A physical inspection will also be performed at the same time I-V data is obtained at the remote sites.

SECTION IV

SCHEDULE

Table 4, the planned implementation schedule, shows that the main impediment to starting routine testing is the delivery schedule of the new modules. According to current best estimates, the last of the scheduled module deliveries will not be made until the end of May 1982, almost 16 months after the first of them were received. Originally, the plan was to start testing all of the modules at the same time, so that they would all be subjected to the same field exposure. Because of the protracted delivery schedule, the plan had to be changed. The revised plan calls for deploying them as soon as possible after receipt. A breakdown of the deployment schedule by module type is shown in Table 5. Once new modules are received, they must be laser-scanned and LAPSS-tested before they can be deployed. And, before routine testing can be started at JPL, the Sandstrom constants must be obtained. It is expected that, barring unforeseen scheduling problems (such as with the LAPSS), the process from receipt to testing at JPL will take about three months. As it now stands, all modules should be under test by the end of August 1982.

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Table 4. Implementation Schedule

	1081												1082												
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	
FORMULATE RESTRUCTURING PLAN						▼																			
DECOMMISSION CONTINENTAL REMOTE SITES																									
CONTRACT TO DECOMMISSION SITES																									
SHIP MODULES AND RECEIVE AT JPL																									
OBTAIN FINAL I V (LAPSSI) DATA																									
REORGANIZE SOUTHERN CALIFORNIA SITES																									
OBTAIN LAST SET OF IN-SITU I V DATA																									
INSTALL NEW STANDS AT GOLDSTONE																									
RELOCATE OLD MODULES AT GOLDSTONE																									
MODIFY EXISTING STANDS FOR NEW MODULES																									
ESTABLISH SITE AT FLORIDA SOLAR ENERGY CENTER																									
REWIRE JPL SITE																									
REMOVE OLD WIRING																									
WIRE IN NEW MULTIPLEXER AND DORIC STATIONS																									
CONNECT DORIC DEVICES																									
CONNECT MODULES TO MULTIPLEXERS																									
FABRICATE INSTALL ARRAY SWITCHING CONTROLS																									
FABRICATE ARRAY DATA LOGGER																									
DEFINE REQUIREMENTS																									
COMPLETE DESIGN																									
CONSTRUCT AND TEST																									
DEPLOY NEW MODULES																									
RECEIVE MODULES FROM VENDORS																									
DEPLOY MODULES AT ALL SITES																									
UPDATE JPL SITE SOFTWARE																									
MODIFY INSOLT AND SUMMARY TASKS																									
REVISE DATA BASE FOR NEW MODULES																									
CODE AND TEST ARRAY1 AND SUMARG																									
START ROUTINE TESTING OF NEW MODULES																									

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Table 5. Module Deployment Schedule

	1981												1982													
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D		
RECEIVE MODULES	b				b	c							d													
OBTAI LAPSS AND LASER SCAN DATA							a						c	b	d		e									
OBTAI LAPSS DATA FOR SANDSTROM CONSTANTS													a	c	b	d	e	g								
RECEIVE SANDSTROM CONSTANTS													a	c	b	d	e	g								
DEPLOY MODULES AT JPL													a	c	b	d	e	g								
CONNECT MODULES TO MULTIPLEXERS													b	c			d	e	f							
OBTAI NEW REFERENCE CELLS																										
START ROUTINE TESTING AT JPL													a	c	b											
DEPLOY MODULES AT REMOTE SITES																										
GOLDSTONE																										
TABLE MOUNTAIN																										
POINT VICENTE																										
CAPE CANAVERAL																										

a MOTOROLA ILA

b G.E. RES

c ARCO SOLAR/LA AUTOMATED ASSEMBLY

d ARCO SOLAR ILA
SPIRE ILA
SOLAREX ILA

e PHOTOWATT ILA

f ARCO SOLAR RES
ASEC ILA

SECTION V

ENDURANCE TEST DATA

A. INTRODUCTION

During the period June 10 to July 4, 1981, the last complete set of I-V data was obtained from the modules at the Southern California sites before they were moved to their new Goldstone location. Typically, the Block I modules had been in the field four and a half years, the Block II modules three and a half years and the Block III modules two and a half years. No data were available from the Point Vicente modules; they had all been stolen in March. An investigation was undertaken but, even though access to the site required entry through a locked and barred gate, no clues were found. Operations at the Coast Guard Facility, on which the site is located, were reduced to a caretaker status last year. This change undoubtedly made the site vulnerable to theft. A security fence has since been installed around the test area.

No performance data was collected from the modules at the Continental Remote Sites this past year. A last set of I-V data will be obtained in the JPL LAPSS facility after they have been received at JPL for final disposition. Results will be reported next year.

B. RESULTS

A final summary of the electrical performance of the Blocks I, II and III modules at JPL, Table Mountain and Goldstone is presented in Table 6. Out of a total of 425 modules* deployed at these sites, 60 have failed, and, at the time the last set of data was taken, an additional 44 were degraded. No distinction was made between newly degraded modules and those that have been on the "degraded" list for a long time, nor was any distinction made between modules that failed outright and those that were previously degraded. A module is considered to have failed when its power is down 25% at least 60% of the time. Included in Table 6 is a breakdown, by quantity and type, of the modules that were relocated to Goldstone, and the modules were kept at JPL. None of the modules being retained for continued testing has degraded.

A breakdown of the degraded modules at the JPL site by power decrement is shown in Table 7. Almost half are Block II Photowatt International, Inc. (formerly Sensor Technology), modules; most of their degradation is due to cracked cells resulting from hail damage. The data in Table 7 were obtained by removing the effects of embedded dirt. This was accomplished by first determining the mean-power decrement of the non-degraded modules of each type and using these data as the basis for removing the effects of dirt. Undegraded silicone-rubber-encapsulated modules' output power could be down

*The GE shingle modules are not included in this total; no individual tests were made on these modules.

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Table 6. Electrical Performance Summary of All Modules

	<i>Sector Tech I</i>	<i>Spectrolab I</i>	<i>Solarcell I</i>	<i>Solar Power I</i>	<i>GE Shingle I</i>	<i>Sector Tech II</i>	<i>Spectrolab II</i>	<i>Solarcell II</i>	<i>Solar Power II</i>	<i>Sector Tech III</i>	<i>Solarcell III</i>	<i>Solar Power III</i>	<i>AEG Solar III</i>	<i>Microlab III</i>	Total
JPL															
No. Deployed	64	41	39	21	40	34	13	19	14	0	0	0	10	8	303
Deployment Period	10/76 12/78	10/76 5/78	10/76 11/77	10/76 12/78	10/78 8/77	2/77 8/77	12/76 11/77	6/77 12/78	5/77 10/77	-	-	-	10/78 2/79	-	-
No. Failed As of 9/80	9	4	8	16	0	2	0	3	2	-	-	-	0	0	44
No. Failed Since 9/80	2	0	1	0	0	2	0	3	0	-	-	-	0	0	8
No. Degraded At Final Acquisition	4	8	1	1	4	14	0	0	3	-	-	-	0	1	32
No. Relocated To Goldstone	14	18	8	0	0	8	9	8	0	8	8	5	5	4	95
No. Retained at JPL	-	18	-	-	-	8	3	4	-	0	-	0	0	0	33
Goldstone															
No. Deployed	14	19	8	6		8	3	4	3	8	4	3	0	0	80
Deployment Period	12/76 4/77	12/76 4/77	12/76	12/76		9/77	4/77	9/77	9/77	1/79	1/79	1/79	-	-	-
No. Failed As of 9/80	0	0	0	6		0	0	0	0	0	0	0	-	-	6
No. Failed Since 9/80	0	0	0	0		0	0	0	1	0	0	0	-	0	1
No. Degraded At Final Acquisition	3	1	1	0		1	1	0	0	1	0	0	-	-	8
No. Retained At Goldstone	7	9	4	0		4	1	4	0	4	4	3	0	0	40
Table Mountain															
No. Deployed	14	18	8	9		8	3	4	3	8	4	3	0	0	82
Deployment Period	11/76 3/77	11/76 3/77	11/76	11/76 11/77		4/77	11/77	9/77	9/77	10/78	10/78	10/78	-	-	-
No. Failed As of 9/80	1	0	0	9		0	0	0	0	0	0	0	-	-	10
No. Failed Since 9/80	0	0	0	0		0	0	0	0	0	0	0	-	-	0
No. Degraded At Final Acquisition	0	0	0	0		2	0	0	1	0	0	1	-	-	4
No. Relocated To Goldstone	7	9	4	0		4	2	4	0	4	4	2	0	0	40

*Only tests of the whole array were made; the exact condition of each module is unknown.

Table 7. Breakdown of Degraded Modules at JPL by Type and Power Decrement

Module Type	Peak-Power Decrement (%)				
	0 to 3	3 to 5	5 to 10	10 to 15	15 to 25
Sensor Tech I	2	1	1		
Spectrolab		4	4		
Solarex I	1				
Solar Power I		1			
Sensor Tech II	3	2	3	4	2
Spectrolab II					
Solarex II					
Solar Power II	1		2		
Arco Solar III					
Motorola III				1	

20% to 30% due to loss in transmittance. If their encapsulation were removed their output power would appear to be undiminished; these modules are not degraded electrically, even though their output power has decreased.

Many of the degraded modules exhibit erratic behavior, often functioning satisfactorily in the morning when cold and poorly in the afternoon when warm. Some have been in a stable, degraded condition for some time and others are constantly changing.

A breakdown of the failure rates, by module type and block procurement, is shown graphically in Figures 13 and 14. No Block III figure is presented because no Block III modules have failed to date. On the Block I figure (Figure 13), two failure-rate ordinate scales are used, one for Solar Power Corp. and one for the other three module types. The Solar Power scale is five times greater--over 85% of the Block I Solar Power modules have failed. Post-mortem analysis indicates that about 80% of these were due to fractured interconnects caused by inadequate stress relief.

A comparative summary of the failure rates of the three block procurements is shown in Figure 15. To put things into perspective, the Block I Solar Power modules were not included in the tally. Surprisingly, the Block I and II curves are similar to one another both in magnitude and shape, particularly as their time in the field increases. The mean composite failure rate for the three procurements is about 2.0% per year, and about 2.7%

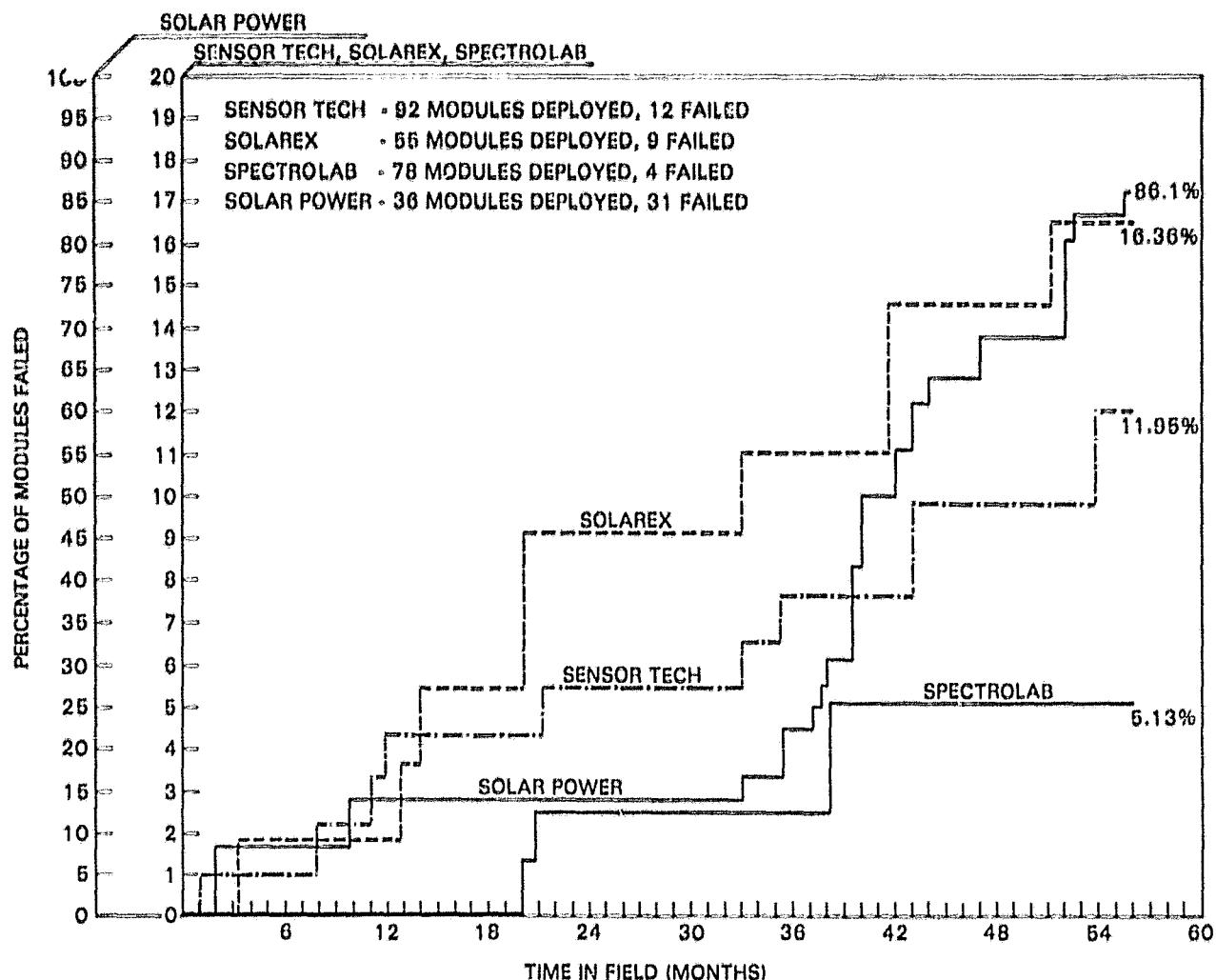


Figure 13. Failure Rate Curves for Block I Modules

excluding Block III. If the last two years of data are used (time in the field between 32 and 56 months), the rate is considerably higher and is closer to 4.4%. This might presage a trend.

There appears to be little correlation between electrical failure and overall physical condition. Many of the modules that failed appeared to be in good physical condition and, of those that appeared to be deteriorated physically the majority still functioned well. An example is the Block II Solar Power modules. Without exception, all have experienced edge delamination, and in many cases, the delamination is extensive, yet failure and degradation statistics show these modules to be no better nor worse than the norm.

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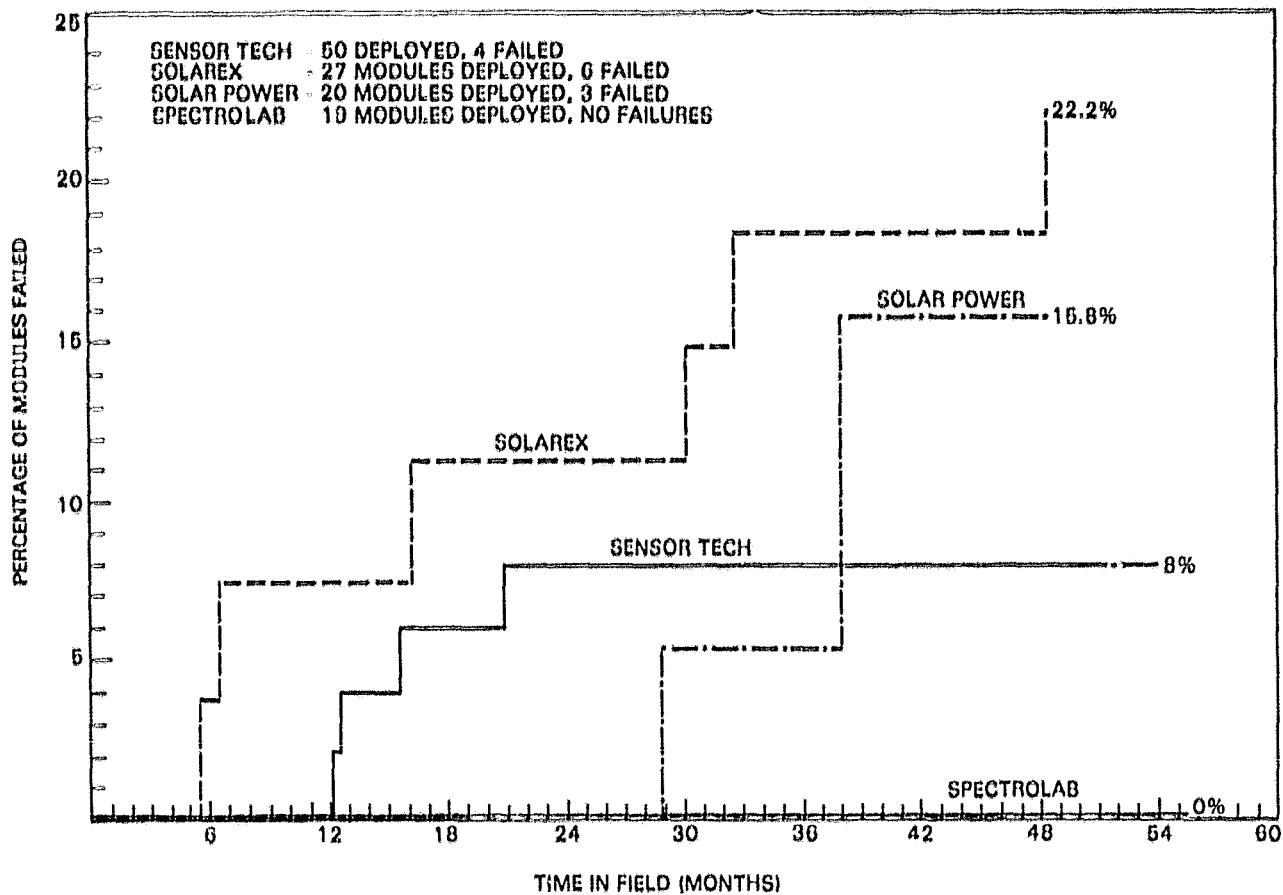
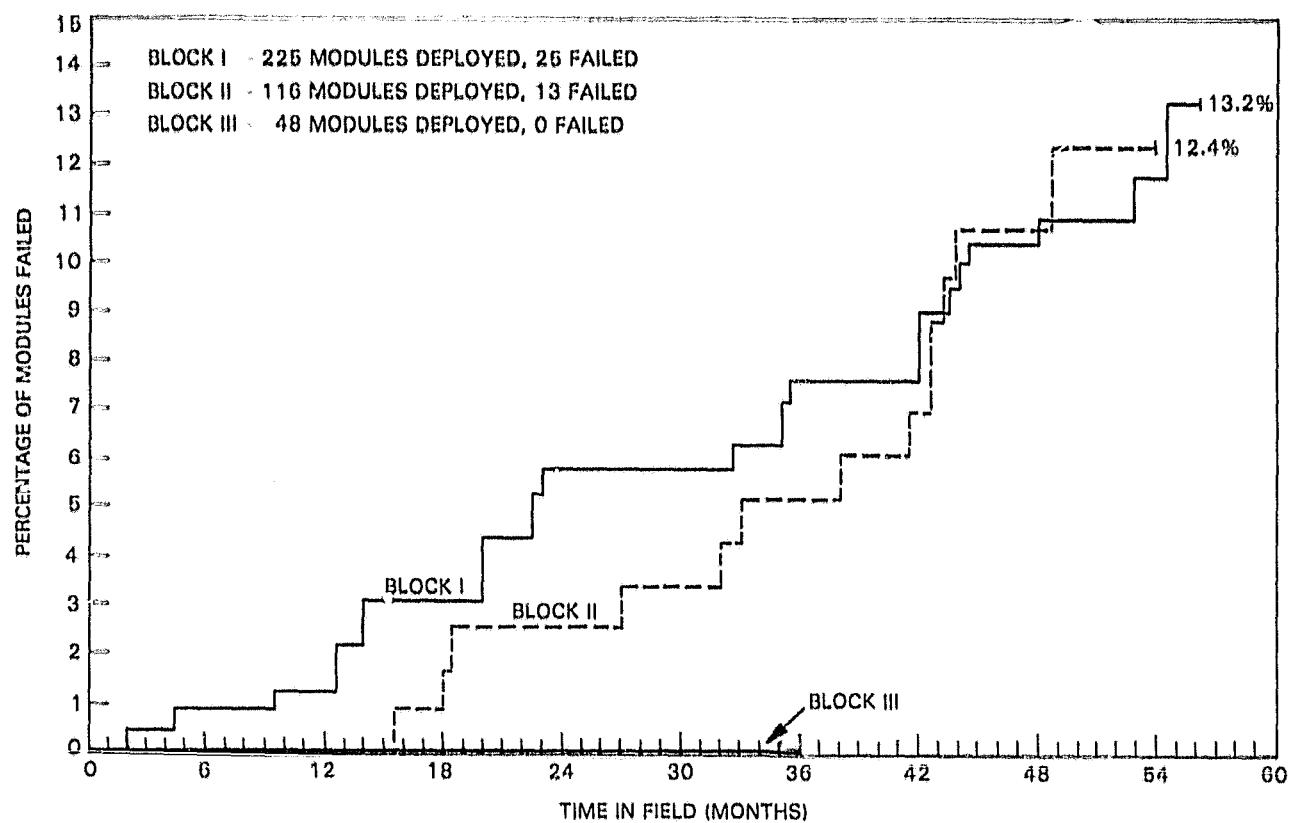


Figure 14. Failure Rate Curves for Block II Modules

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SOLAR POWER BLOCK I NOT INCLUDED

Figure 15. Failure Rate Curves for Blocks I, II and III Modules

SECTION VI

SPECIAL CAPABILITIES AND STUDIES

In addition to reorganizing and restructuring the JPL site network, certain measurement capabilities were added to the JPL site; a diffuse sky-effects study was initiated and plans were developed for some special studies that will lead to a better understanding of module performance.

A. NEW INSOLATION AND ATMOSPHERIC MEASUREMENT CAPABILITIES

In the past, considerable difficulty has arisen in translating module performance data accurately from the test insolation to a reference insolation. The accuracy with which module degradation is determined is directly related to the accuracy of the translation process. The basic problem is in the determination of the appropriate effective irradiance to be used for each module. Experience has shown that differences in the effective irradiance, as sensed by modules and their corresponding reference cells, can be as great as $\pm 3\%$ under different sky conditions.

To gain a better understanding of the problem, and ultimately to improve the accuracy of degradation data, sky characteristics are documented. The data that will be obtained are the direct normal, total normal, total horizontal and fixed-tilt total insolation values, and turbidity, water content and air mass. To obtain these data, a sun tracker was installed and the existing pyranometer stand was modified to accommodate the appropriate instruments. The location of these stands is shown in Figure 4. The sun tracker is computer-driven, using the sun location equations based on day of the year, time of day, sun declination angle, equation of time, latitude and longitude. The tracker has been calibrated and found to track the sun's position to an accuracy of $\pm 0.25^\circ$.

A normal incidence pyrheliometer (Eppley NIP), a precision spectral pyranometer (Eppley PSP) and a filtered radiometer (designed and built in-house by Section 341, Solar Energy Conversion Systems) were mounted on the tracker. Figure 16 shows these instruments as mounted. The filtered radiometer provides the turbidity coefficient and water content of the atmosphere, from the outputs of three radiometers filtered at wave lengths of 500, 858 and 940 nanometers and the equations of Volz and Angstrom.

Mounted on the pyranometer stand are two Eppley PSPs, one horizontal and one at the tilt angle of the modules in the field (34°), and two Li-Cor 200s, one horizontal and one at the tilt angle. A reference cell of each type will be mounted on this stand at the 34° tilt angle.

Data will be sampled from all of these devices every 5 min from sunrise to sunset by means of the INSOLT program and will be summarized daily by SUMAR2 and stored permanently on magnetic tape. The current plan is to develop software that will use these data and the corresponding module data to determine if there is a predictable correlation between the nature of the insolation and the module output. The data will also be used to support other studies such as diffuse-sky effects or spectral-response investigations.

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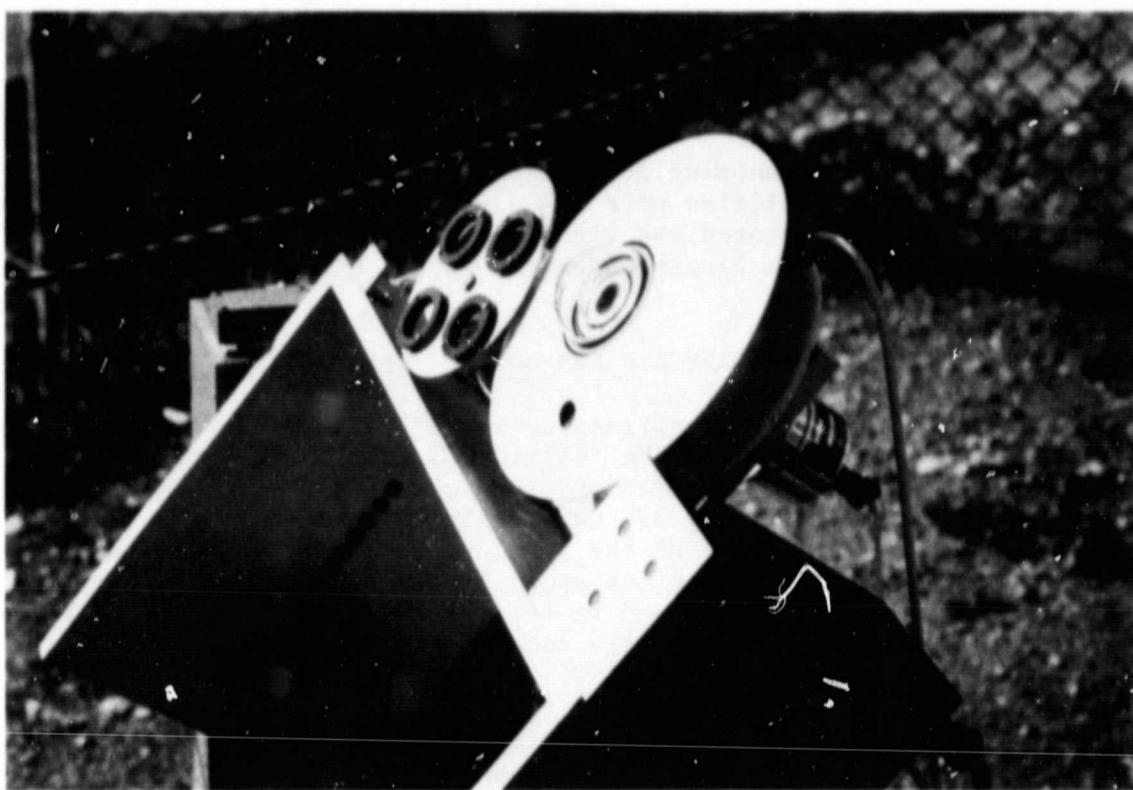


Figure 16. Solar Tracker (l to r: Eppley NIP, Eppley PSP, JPL Turbidity Instrument)

B. DIFFUSE SKY AND SHADOWING EFFECTS

The design criteria for PV installations with many rows of arrays has not heretofore taken into consideration the possible shadowing of portions of the diffuse sky irradiance. Under certain conditions of row-spacing and tilt angle, the lower portion of an array may receive less radiation than the upper portion because a part of the sky is blocked by the array in front of it. On December 23, 1980, an experiment was conducted at the JPL site (latitude 34°) to determine the magnitude of this variation. On that day, there was a high thin, fairly uniform cloud layer. This could be classified as a uniform diffuse sky with a high diffuse-to-direct insolation ratio. The arrays were tilted to 54° and were separated by a distance equal to two slant heights (see Figure 17). The results indicated that the insolation at the bottom of the array was between 10% and 12% less than that at the top. The importance of these findings relative to the layout of, and wiring design for, modules in arrays is obvious. The implication of these findings on the process of translating performance data is equally important and is discussed below. Based on these results, it was decided that further investigation of the diffuse sky shadowing problem was warranted.

The first phase of the investigation was to determine analytically the effects of array row separation distance and tilt angle on the amount of the sky that would be shadowed. This phase was completed and is discussed below. The second phase will be to determine the amount of insolation from the

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various portions of the sky as a function of time of year, time of day and sky conditions. The third phase will be to categorize diffuse sky radiation and combine the results with the separation and tilt-angle array geometry effects to determine the net loss of available energy on the array due to shadowing.

The geometry effects of array row separation distance and tilt angle are summarized in the plot in Figure 17. The plot shows the percentage of available sky shadowed by an array in front of another for a given tilt angle and row separation distance. The data presented are for the middle of an array that is at least six slant heights long. Figure 18 shows the distribution of diffuse insolation lost due to shadowing on the face of the array at the same location as in Figure 17 and at a tilt angle of 35°. If the diffuse-to-total insolation ratio is known and a uniform diffuse sky is assumed, the percent of insolation lost to diffuse shadowing can be determined from Figure 17. For example, if the diffuse-to-total ratio is 0.3 at a tilt angle of 34° and the separation distance is 2 slant-heights, the insolation lost to diffuse shadowing is about 2.2% [0.3 x 0.072 (from Figure 17)]. And, using Figure 18, the bottom of an array would receive about 4.5% less insolation than the top. The effect on module or array output is obvious. Also, the accuracy of translating performance data to a reference insolation value obtained from reference cells that are mounted in unshadowed areas, such as the top of the array, will be adversely affected. In the above example, the insolation used to translate the data to reference conditions would be more than 2% higher than the mean insolation received by the array, and the results of the translation would indicate lower performance than actually existed. This error would be even greater, depending on how the modules were placed and wired in the array, because of the 4.5% lower insolation at the bottom of the array. For instance,

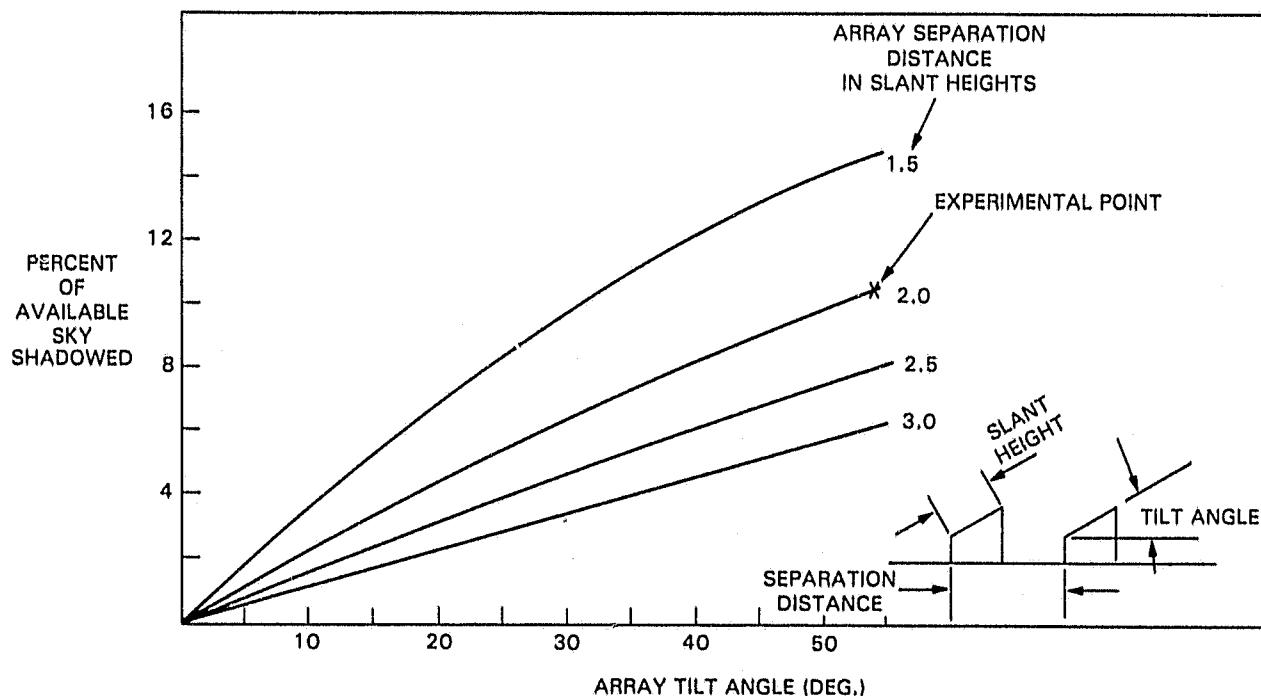


Figure 17. Tilt-Angle and Separation-Distance Effects on Diffuse Sky

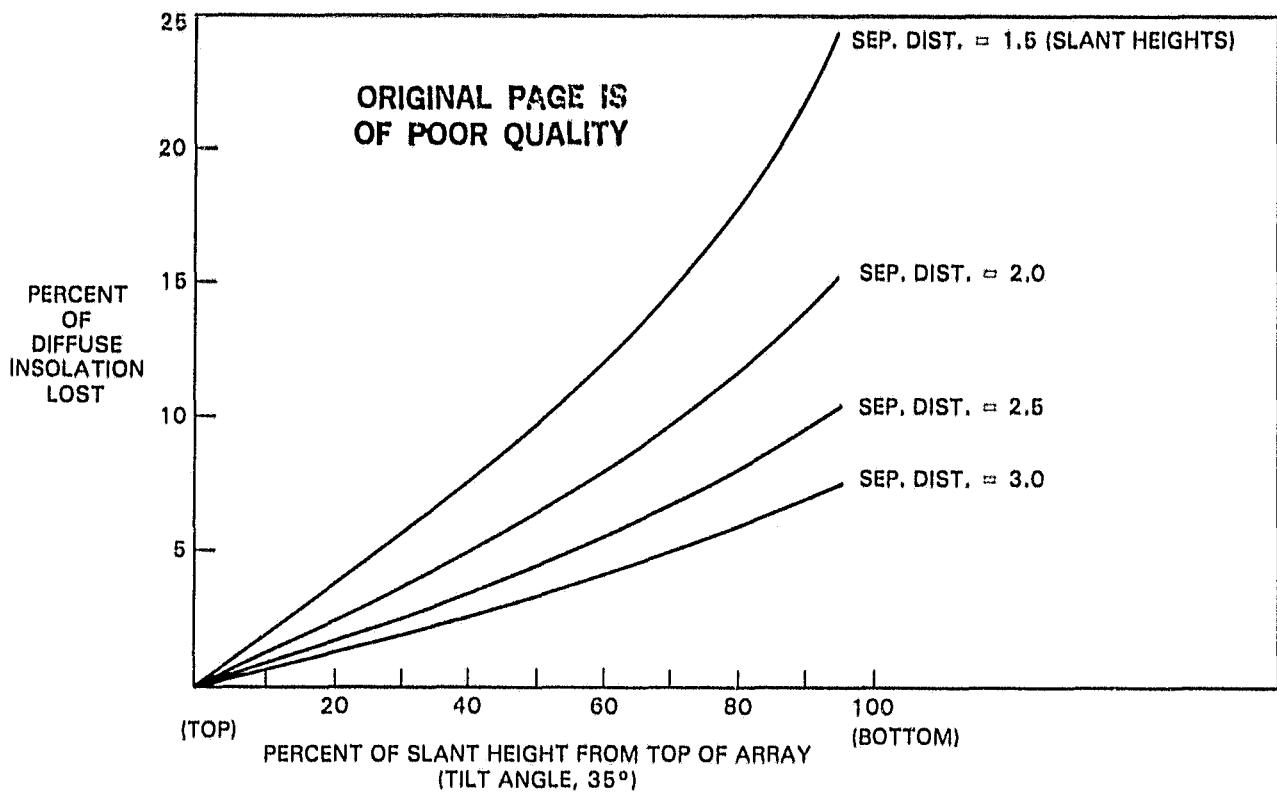


Figure 18. Percentage of Diffuse Insolation Lost Due to Shadowing

if the modules were series-wired in the array, the lower insolation at the bottom would dictate the string current, which would be 4.5% less than an unshadowed array.

When the conditions under which the experiment was conducted (i.e., a tilt angle of 54° and a separation of two slant heights) are used as entry points on the plot in Figure 17 (this point is denoted on the plot), the resulting percentage of available sky shadowed is about 10.2. This correlates favorably with the results of the experiment. The problem of accurately determining total insolation is further complicated by the fact that the diffuse sky is not uniform except during totally overcast periods. To understand and account for this non-uniformity better, studies of the distribution of insolation intensity in the diffuse sky will be undertaken. The results expected from these studies will be methods that can be used for classifying sky conditions and for adjusting performance data.

C. ARRAY PROBLEM SIMULATION

Serious problems have arisen in real-use array applications that have not been detected in qualification and endurance testing. It is essential, therefore, that modules be tested in array configurations if real-use problems are to be identified and ultimately corrected. A facility for performing array simulation must meet two requirements: it must have the capability of

monitoring the performance of arrays and modules accurately to achieve early detection of the problem, and when performance degradation or failure is detected, it must have the capability of quickly and accurately simulating the conditions under which the problem occurred.

The array test facility at the JPL site has the instrumentation for accurately monitoring the performance of arrays and modules and the wiring flexibility to configure arrays into almost any operational condition required. Data obtained in this facility will reflect real-use conditions, but in a laboratory setting. Additionally, when the array data logger is completed, it will be used not only at JPL but also to monitor arrays and modules at sites throughout the country not controlled by JPL. Requests for this new monitoring service have already been received at JPL and have been directed into the appropriate channels. The data obtained from these sites will be of benefit to the managers of the installations and the module manufacturers alike, and will serve to broaden the module-problem data base relative to the various operating conditions represented. The capabilities of the array data logger are such that most concentrator systems could also be monitored.

When a problem is detected either in one of the JPL site arrays or elsewhere, the operating conditions under which the problem occurred will be duplicated as closely as possible at the JPL site. That array will then be monitored more frequently to determine the exact operating point under which the problem arises. Using the data obtained from this simulation, it will be determined whether the problem is one of a kind or is generic to the design of the modules or the array, or to the conditions under which the array operates.

The facility will also be used to conduct experiments to determine the effects of various types of failures that have occurred in the past. Cracked cells and broken interconnects are two of the more frequent problems that have been found in modules over the last few years. A module that is either known to have a problem or one that has been purposely altered to a problem state could be placed in the appropriate array in the test facility. The effects of this module being in the array would then be determined, e.g., changes in array performance, the effect on other modules, or continued degradation of the problem module and its consequences.

Information of this type is valuable not only to the FSA Project but also to the manufacturer and users of PV modules and systems.